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THE KATMAI REGION, ALASKA, AND THE GREAT ERUPTION OF 1912

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In June, 1912, Mount Katmai was the scene of one of the greatest volcanic eruptions known in history. The material ejected, mostly in the form of pumice and fragmental glass, formed deposits whose total volume has been calculated to amount to nearly five cubic miles.[1] At the town of Kodiak, a hundred miles away, this fragmental material ("ash") fell to the depth of nearly a foot, and nearer to the volcano hundreds of square miles of territory were completely devastated.

General knowledge of the effects of this eruption has been derived chiefly from the explorations of several expeditions sent out by the National Geographic Society, the first one under G. C. Martin and later ones under R. F. Griggs.[2] The expedition of the summer of 1919 was planned on a considerably more ambitious scale than former ones, and an invitation was extended to the Geophysical Laboratory to co-operate in the scientific work.

[1] G. C. Martin, "The Recent Eruption of Katmai Volcano in Alaska," *National Geographic Magazine*, Vol. XXIV (February, 1913), No. 2, p. 131.

[2] G. C. Martin, *Nat. Geog. Mag.*, Vol. XXIV (February, 1913), No. 2, p. 131; R. F. Griggs, *Nat. Geog. Mag.*, Vol. XXXI (January, 1917), No. 1, p. 13; and Vol. XXXIII (February, 1918), No. 2, p. 115; *Ohio Journal of Science*, Vol. XIX (1918), p. 2.

Under this arrangement E. T. Allen, E. G. Zies, and C. N. Fenner joined the party for the purpose of studying the chemical and geological phenomena. Previous to our departure for the Katmai region the publications of Dr. Martin and of Professor Griggs and the information obtained from conversations with them were of much assistance to us in making plans for the trip, and, while we were on the ground, Professor Griggs's knowledge of the region and its phenomena continued to be of great service. The party spent about two months and a half in the field, which is about as long a working season as is practicable.

Since the return to Washington, much time has been given to the study of the materials collected, and a full report will be published later. In advance of such publication, however, it has been thought that a shorter article, descriptive of some of the features of chief geologic importance, may be of interest, and is here presented. Necessarily in this brief treatment, many matters to which attention has been paid in our work will be omitted entirely, and in the case of others the basis for conclusions will be presented in brief form only. Fuller discussion must be reserved for the more comprehensive articles to follow.

TOPOGRAPHY AND GENERAL GEOLOGY

The Katmai country is situated near the base of the Alaska peninsula—that long arm which extends southwestwardly from the southern shore of continental Alaska and, with the Aleutian Islands, reaches nearly to Kamchatka (Fig. 1).

Previous to the eruption of 1912, the Katmai region, though difficult of access, was not entirely unknown. On the Pacific side of the volcanic range was the small native village of Katmai, not more than twenty miles from the volcano. On the Bering Sea slope, at the head of Naknek Lakes, was the similar village of Savonoski. Between them ran a trail which had probably been traveled by the natives for many years, and more recently had been used fairly frequently by white men as a means of crossing the peninsula. In 1898 J. E. Spurr, of the United States Geological Survey, led a party over the Katmai trail, but observed nothing which might be considered to indicate that the preliminary pro-

cesses leading to the eruption were at work except that near the summit of the Pass the party experienced several earthquake shocks. Spurr's record[1] is of much value, however, for the information it gives on the general character of the country. Their route lay through the midst of the area that was subsequently devastated. Further reference to this report will be made later.

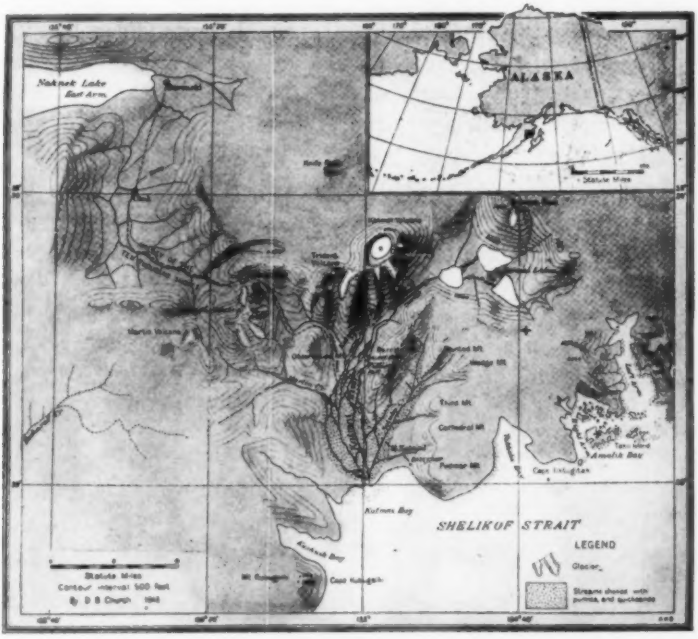

FIG. 1.—Sketch map of the Katmai region. By courtesy of the National Geographic Society.

In the Katmai country and its vicinity the volcanic mountains occupy a comparatively narrow strip of territory approximately parallel with the coast line, bounded on both the northwest and southeast sides by areas of predominantly sedimentary rocks. These sedimentary areas exhibit many forms of mountainous

[1] J. E. Spurr, "A Reconnaissance in Southwestern Alaska in 1898," *Twentieth Annual Report, U.S. Geological Survey* (1898–99), Part VII, pp. 31–264.

relief, and the higher summits are but little inferior in elevation to those of the volcanic belt, but dissection has here reached a stage at which broad valleys of moderate slope have been developed.

The line along which arise the active or recently active volcanoes is one of the longest and most clearly defined volcanic chains in the world. At its northeast end the farthermost volcano whose character is definitely known is Mount Redoubt, though Mount Spurr, Black Peak, and Double Peak, from their position and characteristics, appear to prolong the range still farther to the northeast. These all lie well in the interior, among characteristically conti-

FIG. 2.—The Katolinat Mountains, between foot of Valley of Ten Thousand Smokes and head of Naknek Lakes. These mountains show sections of Upper Jurassic shale and sandstone, several thousand feet in thickness, in horizontal strata. Postglacial canyon in foreground. Photograph by J. D. Sayre, 1918.

nental structural features. Thence the range runs southwestwardly to the base of the Alaska peninsula, and follows the latter throughout its length. Here its course lies through a region of nearly horizontal sediments at only a moderate distance from the edge of the continental shelf, but where, at about the end of the Alaska peninsula, the edge of the shelf curves to the northward, the line of volcanoes continues without deviation and strikes off across oceanic deeps of 1,000 to 2,000 fathoms. The Aleutian Islands and their volcanoes form the summits of a narrow, steep-sided ridge, with great depths of water on both sides. The well-defined character and continuity of this volcanic belt were noted by I. C.

Russell, who says: "This belt of igneous activity is nearly 1,600 miles long. . . . . It is so narrow and well defined that two parallel lines drawn on a map of Alaska, twenty-five miles apart, may be made to include nearly every volcano in the belt that is known to have been active in historic times."[1]

It seems that such a linear distribution must indicate a major fracture in the earth's crust, and we might expect to find plain

FIG. 3.—View across canyon of Katmai River, from lower slopes of Mount Katmai, looking at Barrier Range. These mountains consist of shale and sandstone, believed to be of Upper Jurassic age, in beds gently inclined away from the observer, with some igneous intrusives. Photograph by D. B. Church, 1916.

evidences of dislocation of strata or even profound disturbances associated with it. On the contrary, very little evidence of this kind is apparent in the region explored by us. On the northwest side of the belt masses of Upper Jurassic sediments (Spurr's Naknek series), 5,000 feet at least in thickness and possibly much more, lie in horizontal, undisturbed strata, whose continuity may often be

[1] I. C. Russell, *Volcanoes of North America*, p. 268.

followed by the eye for miles along the mountain sides. A typical mountain block of horizontal sediments is shown in Figure 2. On the southeast side of the range the sediments are still the shales and sandstones of the Upper Jurassic, little different lithologically or paleontologically from those on the other side. Structurally, however, this fact is observable—that they dip fairly uniformly away from the range at angles of 10 to 15°. Some typical views

FIG. 4.—Looking up canyon of Katmai River from Prospect Point. On the left, Mount Katmai in the background, and its lava slopes and cliffs in the middle distance; on the right, the sediments of the Barrier Range. Just above the river level and at the foot of the lava cliffs, surfaces of glaciated sandstone (shown in Fig. 5) were found. Photograph by D. B. Church, 1916.

are shown in Figures 3 and 4. This difference of attitude of the beds on the two sides of the range may indicate block-faulting and tilting, but this seems remarkably slight evidence to be the only indication of a break of such great length and reaching to profound depths. That profound depths have been reached is indicated by the manner in which the break extends without deviation across fundamentally different surface structures. There is, however, a possibility that the volcanic chain may be situated not directly along the surface trace of the major fracture, but

along a system of accompanying breaks. Such a relation appears to be not uncommon in other volcanic districts.

The Katmai group of volcanoes has evidently been built up on a platform of Upper Jurassic sediments, and several features show that comparatively recent flows have produced marked changes of topography. For instance, the canyon of Katmai River (shown in Fig. 4) is a narrow defile connecting open valleys above and below. It is evident that a former open valley here was invaded by floods of lava coming down from Mount Katmai, which shifted

FIG. 5.—Lava flow of basic andesite overlying glaciated sandstone and a small remnant of till (at pick), at foot of the lava cliffs shown in Figure 4. Photograph by R. F. Griggs, 1919.

the river over upon the lower slopes of the Barrier Range. The river has again cut nearly to grade along a narrow canyon, and beneath the lava-flows may be seen beds of till and sandstone surfaces grooved and polished by glacial action (Fig. 5). In this vicinity lava-flows of apparently post-glacial age measure 1,500 to 2,000 feet in thickness (see Fig. 4).

The lavas of the group of cones that we are considering seem to be predominantly basic andesites. In Mount Katmai itself the succession of flows that have built up the cone is now revealed in the great crater pit, and they appear to be of medium to basic character. The fragments of old rocks thrown out with the new lava in the

recent eruption are likewise of this composition, as are also the materials composing the bowlder beds at the rim of the crater (which probably represent a ground moraine whose components were transported by glaciers from the now annihilated upper slopes of the mountain). The testimony from all sources is concordant and demonstrates with a reasonable degree of certainty that Katmai is predominantly andesitic throughout.

In addition to the lavas that have built up these cones, however, there seem to have been other products thrown out by them. In several places near the lower end of the Valley of Ten Thousand Smokes recent stream-cuttings show peat beds interstratified with many narrow bands of siliceous pumice. Probably the rhyolitic lava ejected in the latest eruption of Katmai was not the first highly siliceous differentiate evolved from the underlying magma.

THE VALLEY OF TEN THOUSAND SMOKES AND ITS GREAT ASH DEPOSIT

According to Spurr's description the portion of the Katmai trail immediately to the northwest of the Pass ran for several miles through a wooded valley of varied topography. During the activities of the eruption, the floor of this valley was covered with a thick deposit of ash and pumice, which in most places has buried every detail of the former topography, and whose surface now forms a gently sloping plain. Thousands of fumaroles have found vent through this deposit and are sending out exhalations of hot gases and vapors. Professor Griggs, who discovered and described these remarkable features, has given to this valley the name "Valley of Ten Thousand Smokes" (Figs. 6 and 7).

This ashy deposit covers the old floor of the valley to a great depth (possibly several hundred feet in certain areas) and extends up over Katmai Pass. Its distribution is shown on the map of the valley.

From the very first explorations of the region by the National Geographic expeditions, Professor Griggs recognized that this deposit is quite distinct from the widespread ash-falls due to the explosive ejection of material from Katmai crater, and that it must be accounted for by the operation of other processes. Because of the fact that, when first discovered, certain of its characteristics

were thought to imply that its formation was the result of the extrusion of a mass of semi-fluid mud, this deposit was termed "the great hot mud-flow," and has been so described.[1]

To the Geophysical Laboratory members of the 1919 expedition the evidence seemed opposed to the idea connoted by the term

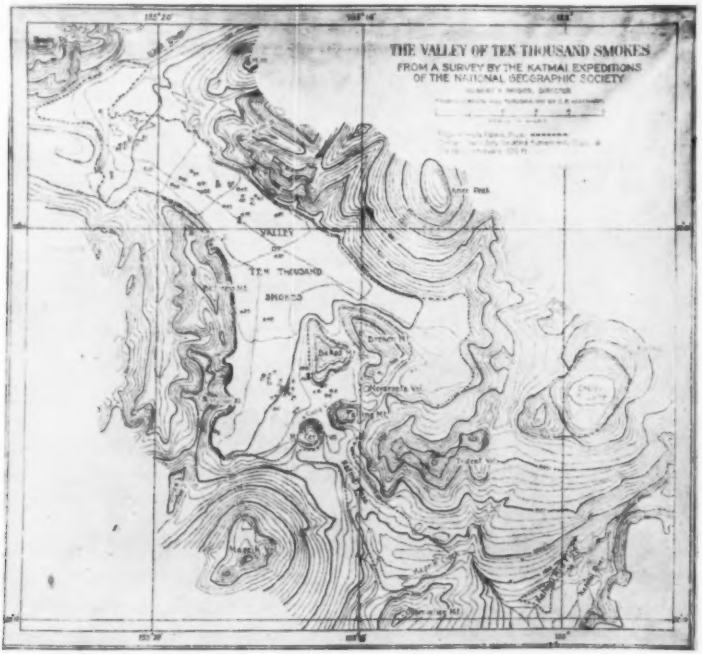

FIG. 6.—Topographic map of the Valley of Ten Thousand Smokes and adjacent region, from surveys made by topographers of National Geographic Society's expeditions.

"mud-flow," and early discussions among us led to the expression of the opinion by Dr. Zies that the evidence was much more in harmony with the idea of the movement of a dry, highly heated mass of sand and pumice than of a water-bearing mud. This

[1] Professor Griggs's article in the *Ohio Journal of Science* (Vol. XIX [December, 1918] No. 2, p. 117) gives an interesting description of this deposit and its remarkable features.

suggestion seemed from the first to have decided merits and later investigations served to strengthen it. Moreover, as evidence of various kinds accumulated, a much more complete conception of the attendant processes was afforded.

The make-up of the deposit itself, its situation with respect to the configuration of the landscape, and various striking effects produced by it demand that certain definite characteristics should be attributed to it at the time of its appearance, and prescribe

FIG. 7.—Looking northerly down the Valley of Ten Thousand Smokes. Photograph by R. F. Griggs, 1917.

rather rigid limitations to one's ideas as to its possible derivation. Observations show plainly that, in the first place, this material was not thrown violently into the air to descend over the general landscape, but that it was restricted very definitely to topographic depressions. In point of time, it was one of the first manifestations of activity, for it is covered by the subsequent ash-falls. The thorough manner in which vegetable material engulfed by it was carbonized and the indications of brush fires started by it can hardly be explained except on the supposition that it possessed a high temperature, probably near incandescence. In many places

adjacent to it but beyond its borders, fallen trees lie as if overthrown by a violent wind accompanying it. This is observable along the margin of the deposit and also on those slopes of the Katolinat Range that lie at the foot of the valley and face up the valley in the direction from which the flow advanced.

Katmai crater could hardly have been its source, as physical obstacles stand in the way of distribution from that point, and

FIG. 8.—The great sand-flow of the Valley of Ten Thousand Smokes, overlain by stratified ash from the Katmai ash-fall; view taken at junction of Knife Creek (at left) and River Lethe (at right, nearly concealed by steam cloud). The stratified terraces just above stream-level are not part of the sand-flow but are the result of recent stream deposition. Photograph by E. G. Zies, 1919.

glaciers that still cover the slopes of Katmai on this side would probably show noticeable effects from the movement of such an incandescent avalanche over their surfaces. The distribution of the material is such that there seems to be almost no escape from the conclusion that it originated within the valley itself and that we must look for its source in vents situated on the floor of the valley or on the lower slopes of the mountains at its head. Such

vents, however, would tend to be concealed by the material that they themselves extruded and by later materials from the ash-falls, and we are not able to point out the exact location of such vents with certainty. It is rather by a process of deduction that our opinions as to their position have been reached.[1]

The vents of extrusion may well have been located along the fissures that are now the seats of fumarolic activity. Support is

FIG. 9.—Carbonized stumps and tundra. The foreground was covered by the sand-flow, but the standing trees in background were beyond its reach. Photograph by E. G. Zies, 1919.

given to this supposition by evidences of former more vigorous activity of a mildly explosive kind at some of these localities. Possibly the newly formed crater of Novarupta in the upper part of the valley was one of the vents, differing from the others only in that it was of larger size than most and that its activity con-

[1] Professor Griggs had previously, in one of his articles, expressed the opinion that the material must have been extruded from fissures within the valley. See article, "The Great Hot Mud Flow of the Valley of Ten Thousand Smokes," by R. F. Griggs, in *Ohio Journal of Science*, Vol. XIX, No. 2, p. 139.

tinued into a stage not represented elsewhere, by which a plug of viscous lava was extruded.

Views of this sand-flow or sand-avalanche and of some of the effects produced are shown in Figures 8–10.

Considering further the origin of the sand-flow, we suppose that rhyolitic magma, charged with dissolved gases, rose to the surface in the newly formed vents. According to general observation the usual course for such a magma is either to retain its gases and form a flow of obsidian, or to evolve them with explosive violence and scatter the disrupted particles to a great distance. In this

FIG. 10.—Trees prostrated as if by wind accompanying sand-flow, though beyond reach of the avalanche of sand itself. Photograph by C. N. Fenner, 1919.

instance, however, it apparently pursued an intermediate course, and produced, by moderately forcible disruption, an outward-spreading and forward-moving torrent of incandescent sand and pumice, each particle of which was surrounded by and partially suspended in gases which it continued to give forth during its impetuous flow.

An artificial reproduction of the properties that are believed to have characterized this ashy material at the time of its extrusion may be obtained by igniting the powder of basic magnesium carbonate. The substance boils in a manner extraordinarily like a liquid, and the gases evolved buoy up the solid particles. In this

condition the mixture exhibits the lack of coherence and readiness to flow that characterize liquids.

The exact counterpart of this deposit does not seem to have been described among volcanic phenomena elsewhere, but the avalanches of incandescent sand and ash that formed prominent

FIG. 11.—Specimen of banded pumice (4×4 inches) from the deposit in the Valley of Ten Thousand Smokes. Adjacent bands show marked differences in composition, as indicated by a silica content of 74.70 per cent in the case of a light band, and 60.40 per cent in an adjacent dark band. The structure is believed to be due to digestion of foreign material.

features of the eruptions of Pelée and La Soufrière in the Antilles in 1902 seem to offer many close analogies. The following quotation from the *Encyclopedia Britannica* gives a statement of the essential features that have been observed in the Peléan eruption:

> Its distinctive character is found in the sudden emission of a dense black cloud of superheated and suffocating gases, heavily charged with incandescent dust, moving with great velocity and accompanied by the discharge of immense volumes of volcanic sand, which are not rained down in the normal manner,

but descend like a hot avalanche. . . . . So much solid matter was suspended in the cloud, that it became too dense to surmount obstacles and behaved rather like a liquid.

Though one may find in the detailed descriptions of these sand-avalanches certain differences from the results seen in the area of the valley flow, they seem to be of degree rather than of kind, and the analogies are striking.

Some of the pieces of pumice in this deposit show a banded or variegated structure, such as is illustrated in Figure 11. The difference of composition of adjacent bands is easily apparent, and in the specimen figured, determinations of silica by Dr. Allen have shown 74.70 per cent in a white band and 60.40 per cent in a dark band. It is believed that these structures are due to a process of partial solution of basic rock in the new siliceous magma. The very limited degree of mixing of solutions shown by these specimens hardly permits us to suppose that the solvent action was long continued; therefore we must look for the source in matter which became involved in the magma when it was near or at the surface and just prior to its foaming-up into pumice. There are several possibilities that should be considered. We might suppose that the sedimentary series beneath the valley had been previously injected by rocks of this description and that these were encountered by the new magma and material absorbed from them; or that the floor of the valley was composed of an old lava flow of basic composition, which contributed material; but the supposition that, for a number of reasons, appears to me the most probable is that the source to which we should look is the deposit of lava bowlders of glacial origin that covered the floor of the valley to a great thickness. The fragments of undissolved andesite found with the ash are probably of the same origin, while the pieces of shale that are quite common in places were doubtless derived from the underlying Naknek sediments. All of these may be duplicated in the lava and ejecta of Novarupta.

THE FUMAROLES

The fumaroles, which are now the most active volcanic features of the region, usually find vent through the unconsolidated deposits

that cover the floor of the valley. In most places they are restricted to the valley floor and few are found on even the lower slopes of the adjacent mountains, but the country within a radius of a mile and a half of Novarupta forms an important exception. In this area, hill and valley alike have been greatly shattered, and are crossed by many steaming fissures. This includes not only the portions of the valley to the east and west of Novarupta, but also Baked Mountain, Broken Mountain, Falling Mountain, and some of the lower slopes of Trident. This area was undoubtedly a scene of the greatest activity during the eruption and is still the site of many fumaroles. Evidently the strains that were here set up in the outer crust have been of sufficient magnitude not only to cause fissures to break through the valley floor but also to shatter the adjacent mountains. In most places, however, they are so restricted to the floor that this topographic depression was evidently a controlling factor, and hence a moderate depth for their place of origin is implied. The phenomena suggest what might be expected from the injection of a sill under a rather small thickness of cover.

The fumaroles were the chief subject of investigation by Dr. Allen and Dr. Zies. They made many measurements of temperatures and collected samples of gases for analysis, and much of interest may be expected when their work is completed. At present the account will be confined to a slight description of a few of the features of the fumaroles. In temperature they run from below the boiling-point of water to a heat more than sufficient to melt lead and zinc. The highest temperature found was 645° C. Among the evolved gases, water usually forms more than 99 per cent. The remainder is mostly hydrogen sulphide, nitrogen, carbon dioxide, and methane. Hydrochloric and other acids are probably present, though in small amounts.

Around the vents sulphur is often found in quantities as a sublimation product, and pyrite in finely divided form is very common. Ammonium chloride also has been collected, as well as crystallized hematite and magnetite, and study of the crusts brought home will probably reveal other fumarolic sublimates. The vents are frequently alined along fissures half a mile to a mile

in length. The velocity of the outpouring gases is seldom very high; commonly their escape is attended by a hissing sound at small vents and a subdued roaring at large ones. A close view of a vent of moderate size is shown in Figure 12. It should not be inferred that all of the water that is evolved is of magmatic origin. The ashy and pumiceous material that forms the upper part of

FIG. 12.—Fumarole No. 42. Baked Mountain and Broken Mountain in the background, and the volcanic range in the far distance. Photograph by E. G. Zies, 1919.

the conduits is soaked with water, and considerable quantities must be vaporized and carried out with the hot gases.

FALLING MOUNTAIN

In the upper part of the valley and not far from Novarupta is Falling Mountain, so called from certain remarkable phenomena which it exhibits. Its northerly face is an almost cliff-like slope, probably 2,000 feet in height, which has plainly been produced by recent slumping off of masses of rock. The volume of material thus removed must have been enormous. At the present time blocks or small masses of rock drop off at short intervals and plunge down the slopes with a succession of sharp crashes, and a

talus pile of considerable size has been built up by such accumulations, but this is of insignificant magnitude in comparison with the total quantity that has been lost to the mountain. Strangely enough, there is little hint as to what has become of this mass of rock. The mantle of ash and pumice that covers the floor of the valley at the foot of the mountain spreads its smooth contours over the whole surface. I think we must conclude that the great rock-avalanche at Falling Mountain was one of the first events accompanying the recent outbreak of volcanic activity, and that it occurred under such conditions of forcible disruption and violent movement that the material was spread widely over the valley floor. The subsequent deposits of ash and pumice, which here are of very great thickness, smoothed out the irregularities left in the surface of the transported material. The rock-falls that we now observe are probably of the nature of after-effects. Remnants of the fissures that were formed at the time of the original disturbances now afford passages for gases and vapors from below. Along these channels the andesitic wall-rock has been powerfully acted upon and transformed into porous aggregates of new minerals, whereby the rock rapidly loses its cohesive strength. It is not surprising to find that among the new minerals tridymite is prominent. The conditions are those under which its formation (as a metastable product) is to be expected. A noticeable effect also is the replacement of many of the pyroxene phenocrysts by aggregates of hematite scales.

These alterations seem to be explicable only on assumptions of rather wide-reaching significance. Apparently the gases that permeate the rocks and that manifest themselves at the surface by the slowly rising vapor clouds are capable of reacting with the constituent minerals in such a way as to form volatile compounds, and the porosity indicates that quantities of material have actually been removed by gaseous transfer. The results of similar processes are visible around the vents of many of the fumaroles on the floor of the valley. Here also there is evidence of the transportation of material in the gaseous medium, and we observe the results of reactions induced by rapidly changing conditions of temperature and composition as the gases approach the

outer surface. The most striking result is the deposition of iron compounds around the vents and in the steamy areas—pyrite, hematite, and magnetite—in quantities which, from the observations of Dr. Allen and Dr. Zies, must be very great in total amount.

When there is brought before us in such striking fashion evidence of the ability of these volcanic gases to transport material, we are naturally led to a consideration of the various circumstances attending the evolution of such gases and the effects that are likely to be accomplished. One query that arises is as to the results of the continual outpouring of such great volumes of vapor as rise from the neighboring peak, Mount Martin, and we may ask whether significant changes of composition are not thereby effected in whatever material may lie at the source from which this vapor proceeds, whether it be a body of magma or material of another sort. Unfortunately, insufficient knowledge of the composition of gases rising from the actual throat of a volcano, as well as of their amount and the length of time over which their escape continues, involves the subject in so much uncertainty that definite conclusions as to the quantitative importance of this process are, as yet, hardly warranted.

THE NEW VOLCANO NOVARUPTA

Near the head of the Valley of Ten Thousand Smokes is the site of Novarupta, a small parasitic vent, which evidently was an exceedingly active volcano during the general eruption, and threw out great quantities of fragmental material, chiefly pumice. Much of this is in much larger masses than those thrown out by Katmai. One such projectile, found about a quarter of a mile away, had a diameter of eight feet. The last act of the vent was to extrude a mass of stiff, viscous glass, which, as it was slowly thrust upward, broke into huge blocks. From a distance this pile of steaming lava-blocks, which is about 800 feet in diameter and 200 feet high, resembles an enormous ash heap. It is surrounded by a circular crater-wall composed of ejected fragments, which is much cut up by actively steaming fissures (see Fig. 13). The material of this is mostly pumice and obsidian, but there are also pieces of shale and sandstone and of dense andesite. The question as to the

manner in which this new vent was developed in the floor of the valley is important. There are undoubted evidences of explosive action, but nothing that may not well be attributed to actions going on after the vent had been opened. What we have to account for here is the formation of a rather small, circular orifice, through which a great amount of pumice was ejected and a small amount of lava was extruded, situated in an area which is much

FIG. 13.—Profile of lower part of Novarupta, and a portion of the inclosing crater wall. Photograph by P. R. Hagelbarger, 1918.

fissured but in which other vents of comparable size are lacking. The formation of an orifice of this description is sometimes attributed to the assumed ability of a subterranean body of magma to perforate by explosive action a great thickness of overlying strata and form a cylindrical pipe or conduit (diatreme) for the escape of lava. It is difficult, however, to form a conception of the manner in which such action has been carried out without attributing to the magma properties for which the evidence seems insufficient. It would be necessary to assume not only that an enormous

amount of energy is set free with great suddenness in a narrowly confined space, but that in some manner this force is given a definitely directed tendency upward. The inherent difficulties in this conception are so great that we naturally look for a simpler explanation.

We might suppose, as a second possibility, that the underlying magma possessed great expansive powers because of dissolved gases which were struggling to escape, and was thus enabled to effect an upheaval of overlying material, but the natural result of this would be the upturning of huge blocks over a rather wide area, and the escape of pumiceous material from many widely open fissures, accompanied by the ejection of portions of the fractured blocks in large masses. No such evidence is visible around Novarupta. The ejection of pumice seems to have been confined mostly to a small opening, and there is no hint in the surface contours of the ash that a widespread chaotic upheaval of strata occurred. Moreover, the largest pieces of ejected sediments found were about the size of one's fist. We turn, therefore, to a third hypothesis, which is really the simplest of all: that fissuring was first produced, either because of regional strain or because of hydrostatic pressure due to the injection of a sill; and that the magma rose along such fissures in much the fashion that any liquid might do, except that a certain amount of solution was effected, and that near the surface a sudden conversion into pumice resulted in the violent abrasion of the walls. Under this conception Novarupta would simply represent a channel along one of the fissures, where chance conditions made escape specially favorable and which therefore tended to enlarge the conduit rapidly and establish more direct connection with the body of magma below. It will appear farther on in this article, as various topics are discussed, that none of the phenomena of the Katmai eruption seem to indicate that these magmas exerted great explosive or expansive powers at depths within the earth, and Novarupta conforms to this idea. Undoubtedly explosions of a violent character occurred here after the magma had reached the surface, but no evidence was found of such explosions prior to its ascent.

The banding present in the lava of the dome that now rises above the vent gives very direct evidence regarding the mechanism of its extrusion. This banding is visible at short intervals around the outer circumference of the dome, where masses of rock in place protrude through the general heap of disrupted blocks, and its direction is found to be parallel with the circular outline of the dome. There is also very good evidence of a process of exfoliation of the outer layers as the central core was forced upward.[1] The character of fracture surfaces of the lava-blocks of the dome is

FIG. 14.—"Cornice structure" in Novarupta lava, produced by fracturing and viscous yielding of the hot mass. Photograph by R. F. Griggs, 1919.

interesting. It shows that many of the fractures occurred while the glass possessed properties of both brittleness and viscosity, such as are shown by stiff tar. This resulted in effects of the kind shown in Figure 14, where the surfaces formed by intersecting fractures have become wrinkled and fluted. The term "cornice structure" suggested itself at once as appropriate for such features.

Many bread-crust bombs are found in the vicinity of Novarupta. These were ejected from the crater as masses of non-vesicular, plastic glass, and the vesicularity developed during the

[1] Compare Harker, *The Natural History of Igneous Rocks* (1909), p. 58, Fig. 8.

short interval of time in which the rapidly cooling mass possessed a rigid crust and a plastic interior. The point to be noted is that the magma, rising into the crater from the depths below, did not immediately puff up into pumiceous masses, but accumulated, at times certainly, in pools of non-vesicular lava. The surprising thing is that this condition held in spite of the relief of pressure. On the other hand, we have evidence that under certain conditions very great pressure did not avail to hold the gases in solution. This is furnished by the lava that was later extruded and now forms the dome. In spite of the enormous pressure to which this

FIG. 15.—Mount Katmai, from the Island Camp. The crater pit extends across nearly the whole space between the two summits. Photograph by R. F. Griggs, 1917.

was subjected during extrusion, the contained gases came out of solution and filled the glass with minute vesicles. The explanation of such phenomena as these will be undertaken later.

MOUNT KATMAI AND ITS EJECTA

Let us consider now some of the features of Mount Katmai, and first the form of the crater as it appears since the eruption. The present appearance of Katmai is shown in Figure 15. Before the eruption the height, as shown by the Coast and Geodetic Survey chart, was 7,500 feet. The top of the mountain has now disappeared and an enormous crater abyss has been formed.

Measurements made by Mr. C. F. Maynard, topographer of the 1917 expedition, give the dimensions of this pit as 2 to 2½ miles in diameter and 2,000 to 3,700 feet in depth. About one-half of the area at the bottom is covered by a sheet of water of a peculiar, milky, turquoise-blue or green color, and from near the center of this lake rises a crescentic island. To one standing on the edge of the pit the cliffs appear almost vertical, but their inclination is probably not more than 60° to 70° on the average. They seem to be made up entirely of a succession of lava flows. On the western side of the rim, for about one-third of the circumference, an ice wall appears—a survival of beheaded glaciers, and the depression in the southern side of the rim is floored with bowlder deposits of morainal origin. The bottom of the crater, where not covered by the lake, appears from above approximately flat. At the foot of the cliffs are talus deposits, which appear of rather insignificant proportions. At present the activity is very slight. Steam rises slowly from a number of fissures and clefts near the bottom, and the water of the lake is evidently warm, but on August 10 snow was lying in many places on the crater floor.

The crater of Katmai is a most wonderful and impressive sight, and photographs give but a very inadequate idea of its tremendous proportions (Fig. 16).

A matter of great interest is that of the mechanism by which this huge pit was formed, for this is intimately related to the question of the volcanic processes attending eruptions. Professor Griggs had recognized the importance of solving this problem and had called particular attention to it before our departure for the region. One's first view would naturally be that the material was blown out bodily in the eruption, but there is good evidence that this is not the whole explanation. A remarkable characteristic of the ejected material is the small dimensions of the fragments. Even on the upper slopes of the mountain there are not many pieces above the diameter of a few inches, and a great proportion of them are much finer. Moreover, almost all the larger pieces are of pumice, and the fragments of older rock have a general maximum size even less than the figures given. Also the proportion of these older andesites is rather small, not nearly sufficient

to account for the mass that has disappeared. Their presence is not likely to be overlooked, as their color—dark red to nearly black—renders them conspicuous objects among the accumulations of light-gray pumice. Since this explanation will not account for the total mass of rock that has disappeared, two other possibilities should be considered: first, solution of the older rock in the new magma; and second, crater subsidence.

Respecting solution, it is believed that this process was very active. That this had occurred was suspected several years ago, as specimens of pumice collected by Professor Griggs on former

FIG. 16.—The crater pit of Katmai. Topographic measurements indicate a diameter of 2 to 2½ miles, and height of cliffs as measured from the level of the lake as 2,000 to 3,700 feet. Photograph by J. D. Sayre, 1919.

expeditions had been examined microscopically by Professor W. J. McCaughey, of Ohio State University, and the presence of basic phenocrysts in the acid magma and the evidences of instability that they manifested had been noted by him. This has now been confirmed independently and much additional evidence has been secured. Various stages of digestion can be followed until the point is reached where quantities of phenocrysts of hornblende, pyroxene, magnetite, and rather basic feldspar are left undissolved in the glassy matrix. In such instances the original groundmass of the basic rocks has been completely dissolved and the phenocrysts are corroded. Plainly such phenocrysts are out of place in

a rock of the composition of that in which they are found. Moreover, pieces of banded and variegated pumice are common, such as those previously described as occurring in the Valley of Ten Thousand Smokes (see page 583), and are attributed to solution of basic rock in the new siliceous magma just prior to ejection. The evidence on these matters will be discussed more fully a little farther on. It appears to show that the new magma, when it rose into the crater, possessed a sufficient degree of superheat to cause it to attack corrosively the basic rock of the crater walls, and, within a brief period, to effect sufficient solution to permit the dispersal throughout its own mass of the basic phenocrysts derived from great quantities of foreign rock-material. The heat requirements seem to demand that in addition to the original store large accessions should have been received, possibly from rising gases.[1]

In any case a new synthetic magma is believed to have been formed in large quantities. The rapidity of destruction of the walls would be attributed to a combination of the shattering effect of explosions and the corrosive action of magma lying in a pool in the crater. The disappearance of much of the rock of the walls may thus be accounted for. Whether all of it may be accounted for by this process and by the ejection of fragments of undissolved rock is not certain. Further evidence will be obtained from analyses (which Dr. Allen has undertaken) of selected material representative of the new magma, little affected by digestion of basic rock; and of other material, representative of the average result attained by the digestion of foreign matter.

The alternative hypothesis, that of crater subsidence, is one in regard to which little or no direct evidence has been observed. Apparently rock-slides of considerable importance have occurred at several places in the crater, due to the failure of the vertical

[1] Daly's discussion of the effect of rising gases (*Igneous Rocks and Their Origin*, p. 267) is rather misleading. It is true that a bubble of gas, expanding and doing work, loses energy approximately equivalent to the work done, but if the work be expended in producing viscous flow in the surrounding magna, the energy lost by the gas is taken up by the magma, and the system as a whole neither gains nor loses. We may therefore disregard expansion and look upon gas rising from below into a cooler region as a source of heat.

cliff-walls to support themselves, but this may be quite independent of a general subsidence of the floor of the crater. We know from Martin's account[1] that natives who had apparently fled from the region almost at the beginning of the activities reported that the top of the mountain was gone. We should hardly expect crater subsidence to take place at this early stage. On the whole, it seems that this idea should be applied only if the process of solution, which, in any case, seems to have occurred on a large scale, appears quantitatively inadequate to account for all the material that has disappeared. At present it seems best to postpone judgment on this until more information is obtained from the analyses.

EVIDENCE AS TO THE NATURE OF THE ERUPTIVE PROCESSES

A study of the ejecta from Katmai and of the characteristics of the deposits that they form supplies considerable additional information on the eruptive processes. When seen in undisturbed deposits at a distance of, say, eight or ten miles from the crater, the ejected matter forms well-defined strata, such as are shown in Figure 17. The component material is chiefly a light-gray pumice in pieces whose dimensions are three to four inches as an ordinary maximum, and run from this to a very minute size. Mingled with this are specimens of banded pumice, dense obsidian, stony andesites, sedimentary shales, and a sort of volcanic conglomerate. Some of the features of these, and their significance, have been touched upon before but will now be considered in more detail.

It was pointed out, in discussing the great sand-flow in the Valley of Ten Thousand Smokes, that the banded and variegated character of some of the pumice indicated a mixture of basic material with the new siliceous magma shortly before extrusion. In such specimens, sharply defined bands adjacent to each other show such differences of composition as are indicated by Dr. Allen's determination of 74.70 per cent silica in one and 60.40 per cent silica in another. The material thrown out from Katmai crater contains similar specimens. The dark bands consist of partly digested basic rock with large quantities of minerals appropriate to andesites.

[1] G. C. Martin, *Nat. Geog. Mag.*, Vol. XXIV (February, 1913), No. 2, p. 147.

A lack of homogeneity on a somewhat larger scale is indicated by the fact that pieces of pumice from the same stratum of the ash-fall show considerable variation from one to another in the amount of basic phenocrysts they carry. These features are significant. It seems as if turbulent motion in the lava when it was liquid would have destroyed such inhomogeneities, especially the sharply defined banding; hence, that solution occurred subsequent to the

FIG. 17.—The stratified Katmai ash-fall, 8 to 10 miles south of the mountain. Note the sharply defined character of the strata. The heterogeneous material on top is the result of a small landslip since the deposition of the ash and pumice. Photograph by B. B. Fulton, 1915.

rise of the lava and while it was standing in a pool not violently agitated. Evidently the magma did not become inflated at once when pressure was removed in the depths of the earth, but rose as a liquid and stood for a certain period in contact with foreign material upon which it acted corrosively.

A careful study has been made to determine the probable source of this basic material. From samples of the ashy strata taken in the field the pumiceous portion, which is greatly preponderant, has been separated. The residue is found to consist principally of

dark, dense material in small fragments. These, to the number of hundreds, have been studied under a binocular magnifier. Their indentification has not been difficult. Sediments excluded, they consist usually of andesites containing small phenocrysts or groups of phenocrysts of plagioclase, hornblende, pyroxene, and magnetite in a felsitic groundmass. In some, however, the phenocrysts are absent. Most are dense but some are vesicular. In microscopic section the small feldspars of the groundmass are frequently seen to be arranged in flow-lines. It is evident that some of the specimens belong definitely to surface types of rocks and all of them may well be such. The possibility that hypabyssal rocks also may be present cannot be wholly excluded, but no evidence of this origin for any of them has been recognized. In composition they are medium to basic andesites, apparently no different from the rocks that form the walls of the crater pit.

Evidence is at hand regarding the absorption of these andesites by the new magma, but before we proceed to consider this matter it is necessary to digress for a moment.

As previously indicated, it is supposed that the fragments of andesite found in the ash-fall, or at least a large proportion of them, represent wall-rock that collapsed and became immersed in the pool of lava. One might expect, therefore, that similar pieces would frequently be found as inclusions in the pumice. This does not seem to be the case; on the contrary, their mode of occurrence is nearly always as detached particles. This is a matter that requires examination, and several features have been noted which have a bearing upon the subject. It is found, first, that not only are inclusions of andesites rare in the pumice but likewise inclusions of shale and of all other dense material except the phenocrysts; second, many of the fragments, although not now inclosed in pumice, present evidences of previous immersion, such as films of glass adhering to their surfaces, and corrosion effects; third, although the pumice does not carry inclusions, the obsidians, which must have been derived from the same lava-pool as the pumice, carry great quantities of both shale and andesite. From these facts it seems that the conclusion to be drawn is not that the andesites were never immersed in the magma, but that, in

the violent explosions, the frothy, semi-liquid pumice and the dense, rigid andesites reacted differently and were forcibly torn apart. The forms of many of the fragments of andesite are such as to suggest fracture by the explosions. If the forces acting upon them were of such magnitude as to produce fracture, it hardly seems surprising that they became separated from the pumice.

Pieces of obsidian, of ordinary maximum dimensions of three to four inches, and of angular shape, were found everywhere in the Katmai ash-fall within the area of coarse ejecta. Many specimens were collected for study, and they furnish interesting information. It is difficult to conceive any origin for them other than the lava pool that gave rise to the pumice; and the presence within them of pieces of pumice (which would inevitably float on the lava) and their general nature suggest that they represent chilled crusts on the surface of the lava. They contain quantities of inclusions of various kinds: sediments, andesites, other obsidian, pumice, and separate crystals. If it be granted that they are fairly representative portions of the lava, the inclusions they contain "frozen in" in all stages of disintegration are of great instructive value.

Another material present in the ash-fall is evidently closely akin to this conglomeratic obsidian. The matrix is semi-pumiceous to glassy, and the numerous inclusions are of the same sort as those in the obsidian. It is interpreted as a surface scum formed over areas of seething lava. The inclusions in this also have been caught in various stages of disintegration.

From the evidence presented by these specimens, the absorption of xenoliths by the magma seems to have taken place in several somewhat different ways. The chemical composition of the fragments and their porosity were probably important factors in the matter. In some instances peripheral solution, especially of the groundmass, seems to have been the principal process, or well-defined tongues of lava may cut off portions and allow them to float away. Probably a more usual form of attack is one involving an intimate penetration of the whole mass. Several factors may have been involved in this: first, that portion of the groundmass of the rock that consolidated last of all and forms a binding-material

among the grains may have had a melting-range little above the temperature of the new magma, and the penetration of the latter and of its vapors was therefore easy; second, an original vesicularity may have been present; and third, a porous condition may have been developed during the history of the rock. The third feature is important. It is not hypothetical, but rests upon observation, and is believed to have considerable significance. It has been found that many of the andesitic fragments in the pumiceous strata have at some former time undergone a process of alteration similar to that described for the rocks of Falling Mountain. Quantities of minute, glistening scales of tridymite have been formed, and a replacement of ferromagnesian minerals by hematite is observable. This carries several implications: first, these mineral transformations are such as might be expected to result from fumarolic action along fissures in the walls of a crater, but not of the kind that would be looked for at great depths; second, the presence of such fissures and the mineral transformations along them would aid in the collapse of the walls during the activities of the eruption; and third, these altered rocks would be more susceptible to penetration by the magma on their immersion in it.

When the process of penetration of magma into porous xenoliths has been thorough, they appear to have become pasty throughout, and what we find is an irregular, lumpy mass, or clot, consisting of basic minerals in a dark groundmass. Under the microscope the phenocrysts are seen to be much corroded. They often contain a great number of inclusions of brown glass, which fairly riddle them, and they look as if they were disintegrating. The groundmass is essentially glassy but contains a multitude of small, irregular fragments or splinters of crystals, and much brown dust. The low index of this glass indicates an acid material in spite of the dark color, and it seems doubtful whether the amount of material actually fused or dissolved was large; the process was rather one of intimate penetration by the new magma, resulting in separation and dispersal of the component minerals and a partial breaking up of crystal units. The low silica-content found by analysis (as in the specimen illustrated in Fig. 11) and the dark color are probably due to undissolved phenocrysts and dust. When the

penetration by the magma reached a fairly advanced stage before the final inflation occurred, these dark masses as well as the light glass assumed the porous condition; both must have been charged with vapors.

Although, under some circumstances, the bands or schlieren that have arisen from these pasty masses remain sharply distinct for several inches and perhaps much more, it is not unusual, on the other hand, for bands to disappear within a short distance. The facility with which the banding has become obliterated in these cases shows that its sharp definition is not a property that persists in spite of turbulent movements.

In the pumice of the early strata of the ash-fall, phenocrysts are almost lacking; in later strata they become exceedingly abundant. Their appearance at this later stage is ascribed to the setting free of phenocrysts from the andesitic wall-rock in the manner described. Their character in the two environments has been carefully compared. Those in the andesites have been studied in microscopic sections, and also under a binocular magnifier in such specimens as show surface corrosion, which has left them in partial relief. The phenocrysts of the pumice have, many of them, been set free by explosions and occur loose in the ashy strata. These are easily studied with the binocular magnifier. Others, still inclosed within a matrix of pumice or obsidian, have been examined in thin sections. In the andesites the phenocrysts occur both as isolated crystals within the felsitic groundmass and as aggregates of the kind that Judd has called glomeroporphyritic groups, and have certain characteristics in regard to size, form, and grouping. The component minerals are pyroxene, hornblende, plagioclase, and magnetite. In the pumice we find the same minerals, isolated or in the same sort of groups as before, apparently duplicating in all respects the phenocrysts of the andesites.

Let us review briefly the evidence that has been presented on this matter. An immense amount of material has disappeared from the top of the mountain and from the crater walls, and must be accounted for. In the pumiceous strata fragments of andesites are found that have the characteristics of surface-flow rocks, and correspond to what is known of the rocks in the crater walls. The

evidence of fumarolic action that many of them bear is in accord with such a situation. These might account for the rock that has disappeared except that they are quantitatively insufficient. We are left, then, to consider crater subsidence versus incorporation in the new magma. Without trying to decide in this article whether *all* of the material may be accounted for by incorporation, the evidence that a large quantity has been taken up in this manner has been considered. According to this evidence, numerous specimens of andesite show attack. The processes involve either an intimate penetration and consequent softening of the whole mass, followed by dispersal of the phenocrysts; or the breaking up of the fragments by attack along fissures, simultaneously with solution of the groundmass around the periphery of the fragments and eventual setting free of the phenocrysts. Finally, multitudes of phenocrysts of the kind that the andesites carried are found to appear in the later strata of the pumice, though the earlier strata are practically free from them. Their instability with respect to their surroundings is indicated by the active disintegration that they are undergoing. The fact that quartz phenocrysts properly belonging to the magma have no association with them is also significant. These facts taken together seem to form strong evidence identifying the phenocrysts of the pumice with those of the former wall-rock, and the disappearance of large quantities of wall-rock is thereby accounted for.

Some of the materials in the ash-strata deserve further attention. The obsidians that have been described, when heated in the laboratory, swell up to a frothy white pumice closely resembling the pumice found in the field. When their powder is heated in a closed tube it yields water, hydrogen sulphide, hydrochloric acid or a chloride, and some gas having a fetid organic odor. It is planned to investigate these gases with care.

Although many phenocrysts of extraneous origin are found in the pumice, the only phenocrysts that properly belong to the magma are quartz and acid plagioclase. These had probably crystallized out before the magma rose into the crater. The quartz, which is easily recognized, is never associated with the groups of xenocrysts mentioned, but, on the contrary, is found in the purest rhyolitic

phases of the pumice. Its presence supplies information regarding the upper limit of temperature within the magma chamber just prior to extrusion. The transition point between quartz and tridymite at atmospheric pressure is 870° C. Probably great pressure will have a perceptible effect in shifting the inversion-point—a thickness of 20,000 feet of rock strata might possibly raise it 100°—but we can be fairly sure that a temperature of less than 1000° prevailed.

The distinctly stratified form of the ash-fall, with its indications of a waning and renewal of activity many times repeated, harmonizes with the other evidence presented that the melted rock accumulated in a pool in the crater rather than that it was discharged as a continuous stream as soon as some hypothetical obstruction, which had previously restrained its escape from the depths, was removed.

From the evidence that has been brought together certain deductions may now be made. We see that the magma, as it issued from the depths of the earth, did not at first show a tendency to evolve its gases explosively; that is, did not have an extremely high vapor-pressure; but that this was developed after a short period of standing under the new conditions, and explosive eruptions ensued. From this we conclude that in the enormous change of conditions consequent upon rapid extrusion internal equilibrium did not keep pace with external changes, and that prior to extrusion such internal combinations prevailed that the tendency of the gases to escape was not extremely great.

As an indication of the depth in the conduit at which explosions occurred the relative amounts of the various sorts of foreign material ejected with the pumice is of interest. Pieces of andesites from the crater walls are very common; fragments of shale and sandstone from the sedimentary platform are frequently found, but the quantity is not so great as of the andesitic rocks; and pieces of deep-seated granitoid rocks are almost lacking, though a few specimens were found. This relative abundance seems to show that the violently explosive action was exerted only at the surface or at a moderate depth in the conduit.

If the renewal of activity at this vent after a long period of quiet were due to an accumulation of imprisoned forces until they reached a magnitude where they were capable of blasting away

obstructions, the bottom layer of ejecta should be made up largely of material from such a source. As a matter of fact this bottom layer is essentially pumiceous and actually appears to be more nearly free of foreign material and more nearly of rhyolitic composition than any layer above it. The view that the close of a period of activity at a volcanic vent is attended by the formation of a plug of lava which seals up the conduit and that the renewal of activity necessitates the clearing out of such a plug, finds little to support it here. Nor, I think, does a consideration of events in certain other explosive eruptions lead to views different from those expressed for Katmai. Many instances might be cited in which for months previous to a paroxysmal eruption manifestations have occurred, such as outbursts of gas and ashes, that can hardly be looked upon otherwise than as indicating a quite direct connection between the surface and the subterranean activity. It seems not unusual, too, for lava to appear in the crater and remain comparatively quiet for a certain period before explosive inflation occurs. The great eruption at Krakatoa in 1883 seems to have followed such a course.[1] At Pelée also there were premonitory symptoms, consisting of an increased evolution of vapors, at times mixed with cinders; later the moderately explosive (though immensely destructive) ejection of the *nuées ardentes*, accompanying the rise of lava in the crater.[2] A somewhat similar course of events may be found in Koto's description of the eruption of Sakura-jima.[3] By what means a volcanic vent can remain sufficiently open to permit a free escape of vapors, without allowing magma to issue, and what conditions finally bring this period to a close and cause a body of gas-charged, actively corrosive magma to appear are matters whose explanation presents many difficulties. No theory of volcanism that I have seen appears at all adequate to account for the phenomena. Indeed, some of the fundamental concepts of current theories seem irreconcilable with them.

Objection may be raised to the somewhat novel idea that has been presented here, of a state of unstable equilibrium of the

[1] J. W. Judd, "The Eruption of Krakatoa and Subsequent Phenomena," *Report of the Krakatoa Committee of the Royal Society*, pp. 11–20.

[2] A. Lacroix, *La Montagne Pelée et ses Eruptions*, pp. 35–39.

[3] B. Koto, *The Great Eruption of Sakura-jima in 1914*, pp. 56–82.

magma, and the question may be asked as to what combinations are supposed to be entered into between the volatile and non-volatile constitutents that would give the required effects, also as to the nature of the changes in the physical environment by which the condition of unstable equilibrium is brought about. These are natural queries, and answers would be eminently desirable; nevertheless, it is believed that the case rests not upon the ability to answer them but rather upon the plain evidence of the phenomena themselves. It may be of assistance, however, to a comprehension of what is meant by unstable equilibrium of the magma, to consider certain familiar phenomena exhibited by obsidians. Any obsidian which, when heated, puffs up into pumice, shows characteristics allied to those that I have ascribed to the Katmai magma. The behavior of the obsidian in this respect indicates that it likewise in its past history underwent changes of condition in which internal equilibrium failed to keep up with external changes. If this were not true it could hardly have retained its dissolved gases but would have evolved them during cooling. In instances of this kind the lack of equilibrium continued even beyond the stage which the Katmai lavas reached, and finally all possibility of evolving gases disappeared because of increasing rigidity, but this result was probably due to factors (such as rate of cooling) which may well be variable. In the case of Katmai and other volcanoes, it seems reasonable to suppose that the magma first experienced very rapid change of conditions during its rise in the conduit, but then remained for a certain period in comparative quiescence, and thus opportunity was given for approximate equilibrium to be reached before a condition of prohibitive rigidity had set in.[1]

From evidence of the kind given it appears that examples of unstable equilibrium in magmas, due to sudden changes of environment, are not at all uncommon. Recognition of this fact and of what it connotes may be helpful in directing inquiry into the conditions that have brought it about.

[1] Interesting examples of the effect of rate of cooling upon the final product in somewhat analogous systems are furnished by Morey's experiments on hydrated alkali silicate melts prepared in steel bombs. Rapid quenching gave a rigid, hydrated, unstable glass, while slow cooling caused the expulsion of dissolved water and the formation of a pumice. See G. W. Morey, *Jour. Amer. Chem. Soc.*, Vol. XXXVI (February, 1914), p. 226.

SUMMARY AND CONCLUSIONS

A preliminary account has been presented of observations made by the writer as geologist of the expedition sent in 1919 by the National Geographic Society, in co-operation with the Geophysical Laboratory, to the Katmai region. As a result of this work many of the observations made by the director of previous expeditions have been confirmed and supplemented. With regard to one or two others, somewhat different interpretations are given in this article from those of previous publications, but it is believed that on these matters also all concerned are now in agreement. With respect to still other phenomena, which had not been previously described, evidence has been found that affords a basis for extending considerably our ideas respecting the processes at work during the eruption.

It has been found that the volcanoes of this region, which form a continuation of the Aleutian loop or festoon, are situated in an area of sedimentary rocks remarkable for the absence of folding or obvious faulting. The more recent lavas are basic andesites, contrasting greatly in composition with the highly siliceous rhyolite of the last eruption.

In the area of the Valley of Ten Thousand Smokes, it is believed that the injection of a sill or closely similar body of magma into the underlying strata at the beginning of the eruption caused shattering of the rocks above it, and these openings permitted the ascent of magma. The extrusion and inflation of this magma gave rise to a great ash- or sand-flow, analogous in many respects to the *nuées ardentes* of Pelée and La Soufrière, and led to the formation of the parasitic cone of Novarupta. The fumaroles are thought to be due to the continued evolution of volatile constituents from this body of magma. The development of the new vent of Novarupta is ascribed to the enlargement of a channel along one of the fissures. The later extrusion of the stiff lava forming the dome of Novarupta is found to have been similar in many respects to that of the "spine" of Pelée.

At Falling Mountain the most interesting features are those resulting from fumarolic action. Evidence of a process of solution and transfer of rock material in the gaseous medium was found

here, and the results of similar processes around the vents of the fumaroles in the valley were observable. It is suggested that the properties of the evolved gases indicated by this gaseous transfer may at times lead to results of great importance in volcanic processes.

A study has been made to determine the manner in which the top of Mount Katmai disappeared and the great crater pit was formed. It seems quite certain that the material was not blown out directly but must be accounted for otherwise. Crater subsidence may have been a factor, but it is believed that collapse of the crater walls and incorporation of the material in the new magma were chief features. It is recognized that the latter process demands a large quantity of heat for its accomplishment, and the magma evidently was not at a very high temperature prior to its ascent; therefore accessions of heat seem to be demanded. A considerable problem is thus presented, but it does not seem at all insuperable, and it is believed that the evidences of solution are so strong that they cannot be disregarded.

One of the important features of the eruption brings up for consideration a phenomenon to whose significance little attention seems to have been paid hitherto. It is that of a gas-charged magma gradually developing the explosive condition after some interval has elapsed subsequent to its ascent from the depths. The Katmai magma seems to have followed this course, and the phenomenon is apparently not uncommon. This is believed to have great significance and to imply changes of physical environment during its ascent, effected with such rapidity that internal readjustments were not able to keep pace with them. Many of the current theories of volcanism are based upon a fundamentally different conception of the nature and properties of the magma. It is thought that it may be advantageous in many cases to consider matters from the new standpoint here suggested.

In other matters also, theories that have been proposed and somewhat widely accepted are apparently not in accord with the evidence found here. It has not been possible in this article to discuss these matters exhaustively, and other matters of interest have not been touched upon. Fuller treatment will be presented in articles to follow.

July, 1920

ON SOME PHYSICAL PROPERTIES OF ICE

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INTRODUCTORY NOTE BY T. C. CHAMBERLIN

While many of the more obvious problems of ice and ice action have been solved in a general way, there remain not a few questions of a more refined sort which require solution before glaciology can rest on a secure foundation. Some of these questions are critically important for they bear radically on interpretations that have already been widely accepted and are currently taught. More extended and more critical field studies are required to solve some of these questions while the solution of others depends on more discriminative and exact laboratory experimentation. All of them call for more searching analyses of the problems themselves, as a source of guidance in field work and in experimentation, as also in the interpretation of results. The glacialists working at Chicago have been trying to do their bit toward the solution of some of these problems and have had under way for some time a series of attacks along several lines in both field and laboratory. This paper presents the preliminary results of a careful series of laboratory determinations carried out by Professor Motonori Matsuyama, of the Department of Geophysics of the Kyoto Imperial University, Japan, who has been spending the year at Chicago.

When McConnell, followed by Mügge, announced that ice crystals are minutely laminated in planes normal to their optical axes and that movement along these planes was notably easier than in other directions, it was felt by many that these disclosures offered a happy solution of the anomaly of glacial movement which seemed to be a quasi-fluidal flow in a body obviously rigid. But later critical studies raised serious doubts as to the actual participation of the gliding planes in ordinary glacial motion, and so the subject came to demand more refined examination. Up to date, no one, so far as I know, has determined what is the measure of the resistance to motion along these planes compared with the stresses actually brought to bear upon them in ordinary glacial motion. Nor has it been shown whether the relation of these gliding planes to one another is of the elastic or the viscous order. But even if these properties were known, there would still remain the radical question whether glacial motion actually takes place by means of movements along these planes—or in any other way *within* the constituent crystals—or whether it is essentially a motion between the constituent crystals. There are here

therefore two quite distinct problems. The investigations of Professor Matsuyama relate to the second of these.

The method of Matsuyama is, so far as I know, unique in that he deals with bundles of crystals which have a common known orientation. He thus brings movement along the gliding planes into experimental competition with movement between the crystals. All are familiar with experiments upon the yield of glacier ice where the mass under test was formed of many crystals of *diverse* orientation, but this very diversity of orientation stood in the way of a strict interpretation of the results. Matsuyama, however, so selected his prisms and cylinders as to force an alternative between combined movement on gliding planes and movement between the crystals. His method and his achievement are therefore notable.

It is further to be observed that in his experimentation he used the torsional method, following Michelson, in which the errors arising from the stretching or compression of the prisms or cylinders are avoided, since the cross-section remained constant throughout the trial. But as check upon the results of torsion, Matsuyama added the method of bending in which stretching on one face and compression on the other were involved. In the interpretation of the results of this method he called in the resources of the petrographic microscope with the discriminating results given in the text.

INTRODUCTION

The motion of an ice sheet along the mountain slopes and over a large area of the Continent may be caused by more or less different forces. Besides the external forces, it is also important to know what is the behavior of the ice itself in such motion. Numerous works have been published on these problems, among which those of McConnell and Mügge are famous and have been referred to by many authors. According to them an ice crystal can be sheared more easily in the direction parallel to the basal plane than in any other direction. The elaborate works of the members of the Cornell University geological staff[1] added important contributions to the same line. Their idea is that the gliding planes of ice crystals arranged parallel to their basal sections control the behavior of an ice mass as the main factor.

Deeley[2] calculated the viscosity of ice from Main's experiment and found its value to be 6×10^{12} c.g.s. at 0° C., while his own observations on Swiss glaciers gave 125×10^{12} c.g.s.

[1] R. S. Tarr and J. L. Rich, *Zeits. f. Glets.*, Vol. VI (1912), pp. 225–49; R. S. Tarr and O. D. von Engeln, *Zeits. f. Glets.*, Vol. IX (1915), pp. 81–139; O. D. von Engeln, *Amer. Jour. Sci.*, Ser. 4, Vol. XL (1915), pp. 449–73.

[2] R. M. Deeley, *Geol. Mag.*, New Ser. 5, Vol. IX (1912), pp. 265–69.

Various investigations related to glacier problems were planned and worked on for many years in this department by Professors T. C. Chamberlin and R. T. Chamberlin. The present work is a part of that series and gives the result of preliminary investigations on the elastic properties of ice. Since torsional force applied to a circular rod is the only type of strain, as Professor Michelson[1] says, in which the cross-section remains constant, the main part of the present study consists of observations on torsional deformation. Later some attempts were made to determine the Young's modulus and also to observe what would happen in bending.

The preliminary work was begun early in the autumn of 1919, but owing to a delay in securing certain necessary apparatus, it was not until about the beginning of February, 1920, that the work really began in earnest. About the end of March it became so warm that it was no longer possible to continue the work on ice. Because the time available for this cold work was so short, the results are to be considered only as preliminary; yet they were so suggestive that the present writer considered it worth while to publish them even with these limitations.

During the research, Professor R. T. Chamberlin took constant interest and gave important suggestions for which the writer is very much obliged.

LIMIT OF ELASTICITY

According to Professor Michelson,[2] the deformation of an elastic body passes through four different stages as it goes on, and in the first portion the deformation is characterized by being approximately proportional to the stress. The limit of this part is well defined in some materials while in others it is not so distinctly marked.[3] The following description will show that ice also has a rather well-defined limit of elasticity in some cases at least.

Method.—In the present experimentation a circular rod of ice was held horizontally with its one end fixed to a rigid stand and the other end attached to a circular disk of radius 7.45 cm. movable

[1] A. A. Michelson, *Jour. Geol.*, Vol. XXV (1917), p. 405.

[2] *Ibid.*

[3] A. E. H. Love, *The Mathematical Theory of Elasticity*, p. 112.

around a knife-edge at its center which rested on a horizontal plane. The whole equipment was kept in a thermos box, the temperature inside of which could be kept low and constant by using freezing mixture. The torsional stress was applied by putting weights on the scale pan hanging from the limb of the circular disk through the bottom of the box. The amount of torsion was observed by means of a telescope through a window in one side of the box.

In the first set of experiments, the test piece was cut out from artificial ice and consisted of parallel crystals with their optic axes transverse to the longer dimension of the bar. The first bar was 13.15 cm. long and 1.73 cm. in mean diameter.

The deformation was found to depend upon the rate of increase of force, especially near and beyond the elastic limit. In the first experiment the force was increased by adding two pieces of weights, each weighing 4.40 gm., every five minutes. The total time duration for this observation was 3.5 hours and meanwhile the temperature was constant at $-7°.0$ C. The observed relation between the weight and deformation is shown in Figure 1.

From this curve one can easily see that a rather marked change of yielding is recognizable at the point B, up to which the strain is more or less proportional to the stress. This feature is none but the characteristic of an elastic curve[1] and we may say that ice behaves like an elastic solid.

Later it was learned that the point B was not so well defined in some cases as in the present one. It is for further study to see when this point will be sharply shown and when not.

MODULUS OF RIGIDITY

Rigidity is the resistance of a material to shearing force and is given by the ratio of the amount of shear to the applied force. If a circular rod of length l and radius a is twisted through an angle Φ by an external couple PL, the modulus of rigidity n will be given[2] by

$$PL=\tfrac{1}{2}\pi n\frac{\Phi}{l}a^4.$$

[1] Given in every book on elasticity.

[2] Poynting and Thomson, *Properties of Matter*, p. 79.

It was found that it took about 10 minutes to reach the new equilibrium position when an ice bar is twisted by a certain stress within the elastic limit. The deformation in the foregoing observation in the part *AB*, therefore, must be slightly modified for this effect. Careful observations were made, increasing the load by the same amount at intervals of 20 minutes. As the result it was found that the mean deviation was 5'.2 per 26 gm. on the

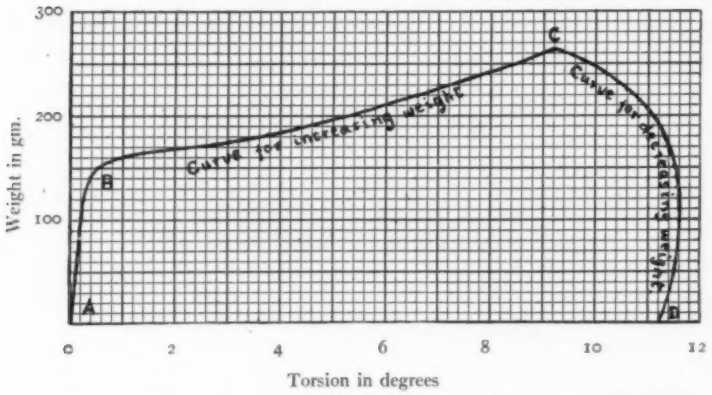

FIG. 1.—Torsion curve of an ice bar, 13.15 cm. long and 1.73 cm. in diameter, with crystals transverse to its longer dimension. Arm of the torsional couple 7.45 cm. Temperature −7°.0C.

scale pan, the temperature being kept at −7°.5 C. From this and other known values of the constants, we obtain

$$n = 1.9 \times 10^6 \text{ c.g.s.}$$

The value of n was calculated from data in several experiments intended primarily for other purposes. The following table gives the values of n thus obtained for ice bars with optic axes of their component crystals transverse to them.

Temp. (C.)	$n \times 10^{-6}$	Temp. (C.)	$n \times 10^{-6}$
−11.7	2.0	−9.3	2.1
−11.7	2.0	−7.5	1.9
−10.0	1.6	−6.7	1.6
−10.0	2.1	−6.7	1.6
− 9.5	2.0	−4.0	1.6

These results seem to show some decrease of rigidity with rising temperature. Near the melting-point of ice, its rigidity will decrease more rapidly than at lower temperatures, so that the rigidity-temperature curve will be concave toward the temperature axis. If we consider rigidity to depend upon the temperature t up to the second power and calculate the coefficients from the foregoing data, we obtain

$$n=(0.18-0.095\,t-0.0020\,t^2)\times 10^6 \quad \text{c.g.s.}$$

This is represented by the curve in the following figure (Fig. 2), the observed points being denoted by crosses.

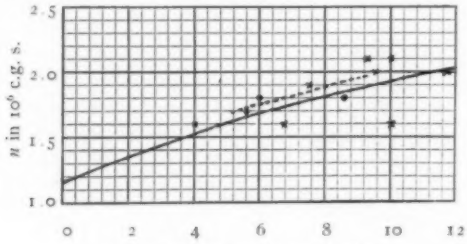

FIG. 2.—Modulus of rigidity of ice composed of parallel crystals at various temperatures. Crosses denote the values when shear is parallel to the optic axes of the crystals and dots the values when shear is parallel to their basal sections.

Similar observations were made for ice bars with the optic axes of the constituent crystals parallel to the axis of the bar. The test piece was 20.95 cm. long and 1.93 cm. in diameter. The crystals were for the most part several millimeters in diameter and never so long as to reach from one end of the bar to the other. The mean deviation was 10′ by 44.0 gm. at −6°.0 C. Using the known values of the constants, the rigidity was calculated to be

$$n=1.8\times 10^6 \text{ c.g.s.}$$

The following table gives the value of n determined from different experiments:

Temp. (C.)	$n\times 10^{-6}$
−9.2	2.1
−8.6	1.8
−6.0	1.8
−5.6	1.7

These data are, by no means, sufficient to determine the relation between the temperature and the rigidity, or to compare this case with the former. As a very rough approximation, however, if we take the means of the first two and the last two and join the points corresponding to them in the figure, we will see that the joining line lies above the curve for the ice bar with transverse crystals. This at least suggests that an ice mass will be deformed more easily when it is twisted parallel to the optic axes of the constituent crystals than when twisted parallel to their basal sec-

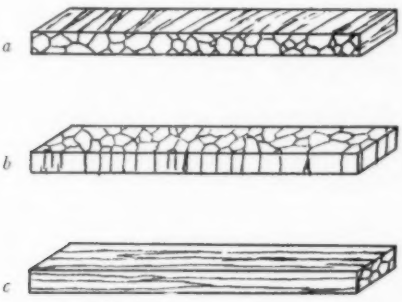

FIG. 3.—Orientations of crystals in test specimens for bending

tions. This result alone is not much to be relied upon. But it is consistent with the results which will be described later.

YOUNG'S MODULUS

Elastic behavior of a solid is determined by two independent elastic constants. We have already found the value of the modulus of rigidity of ice. It is desirable to find also the other, or Young's modulus, which is the resistance of a wire to elongation defined as the ratio of the stress to the strain. To determine this, the usual method of bending was used, with two mirrors and the scale-and-telescope method.[1]

The test specimens were bars of ice with rectangular cross-section (Fig. 3). The component crystals were arranged either (*a*) horizontally or (*b*) vertically transverse to the bar, or else

[1] Poynting and Thomson, *Properties of Matter*, p. 100.

(*c*) parallel to the length of the bar. Since, as we will see later, ice is affected by the phenomena of elastic fatigue, a new bar was generally prepared for each experiment. These bars were not always of the same magnitude; the bar 1*a* was made by cutting bar 1 in half to see if we could get the same result. The results of several observations are given in the following table:

Specimen No.	Orient.	Length cm.	Width cm.	Thickness cm.	Temp. (C.)	Young's Mod. 10^6 c.g.s.
1	*a*	31.0	1.58	.95	−5.0	11.2
1*a*	*a*	15.0	1.58	.95	−4.8	10.5
2	*a*	18.0	1.87	1.05	−2.0	6.0
3	*b*	22.5	1.73	.85	−3.0	6.0
4	*b*	18.0	1.80	1.02	−2.2	5.9
5	*c*	22.2	1.62	.83	−4.0	18.9
6	*c*	11.0	1.25	.76	−4.1	16.6
6*a*	*c*	11.0	1.25	.76	−3.0	20.0

It will not be safe to consider the effect of temperature upon Young's modulus in each case from these few determinations. Since the range of temperature in these observations is not very large, we may consider the mean values for each case not very far from the truth. These mean values are:

Orient.	Temp. (C.)	Young's Mod. 10^6 c.g.s.
a	−3.9	9.2
b	−2.6	6.0
c	−3.7	18.5

Here it is clearly shown that the specimens of orientation *c* whose crystals are parallel to the long dimension of the bar have the largest value of Young's modulus. We have already seen that the modulus of rigidity seemed greater when shear is parallel to the basal section of the constituent crystals than when perpendicular to it. These results have very important meaning in considering the behavior of an aggregate of ice crystals. If the gliding planes of an ice crystal parallel to the basal plane are the main factor determining the behavior of an aggregation of ice crystals under deforming forces, we must expect that ice will be deformed

most easily when the deforming force is parallel to the basal planes of the constituent crystals. The present result shows the reverse fact which suggests that there must be some other factor controlling the deformation.

It is interesting to compare the values of elastic constants of ice with those of other materials.[1]

Material	Rigidity	Young's Mod.
Steel	8.12×10^{11}	20.9×10^{11}
Lead	0.56×10^{11}	1.62×10^{11}
Glass	$3. \times 10^{11}$	$7. \times 10^{11}$
India rubber	1.6×10^{7}	$5. \times 10^{9}$
Ice (*a*)	1.6×10^{6}	9.2×10^{6}
(*b*)		$6.0 \times 10^{}$
(*c*)	1.8×10^{6}	18.5×10^{6}

Thus we see that ice has much smaller elastic constants than metals and very small even compared to india rubber. For metals the value of Young's modulus is generally about three times as large as that of rigidity. For india rubber it is about three hundred times as great. For ice, the value of Young's modulus is from four to ten times as great as the rigidity, depending upon the orientation of the constituent crystals.

TORSION BY CONSTANT FORCE

As long as it remains within the limit of perfect elasticity, the deformation will little depend upon time. After that it will take considerable time before the final position of equilibrium is reached under a given force. For the purpose of finding the mode of yielding by constant force, a circular rod of ice with crystals transverse to it was twisted by different amount of torsional couple. The rod was 20.85 cm. long and 1.96 cm. in mean diameter. The torsional angle was observed at various times after a certain amount of weight was put on the hanging scale pan. The yielding curves under different weights are given in Figure 4.

As to the law of elastico-viscous flow of solids, Professor Michelson has published the results of his elaborate work with a formula which is to be used for materials of widely different properties.[2]

[1] C. W. C. Kaye and T. H. Laby, *Physical and Chemical Constants*, p. 27.

[2] A. A. Michelson, *Jour. Geol.*, Vol. XXV (1917), pp. 405–10, and Vol. XXVIII (1920), pp. 18–24.

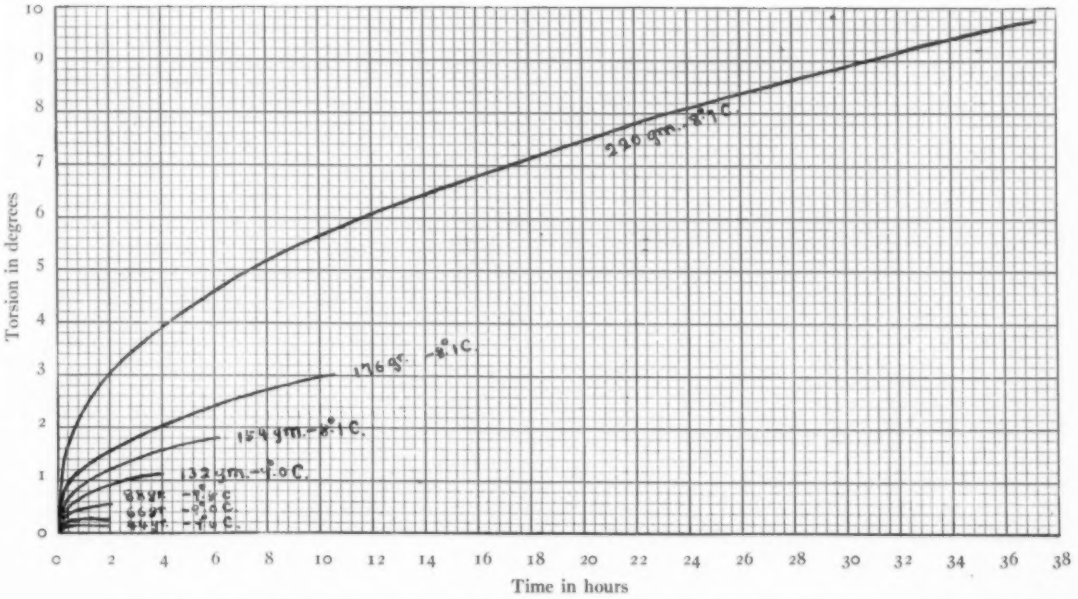

FIG. 4.—Torsion curves, by constant forces, of a circular ice bar, 20.85 cm. long and 1.96 cm. in diameter with crystals transverse to its longer dimension.

If we calculate the values of constants for that formula from the foregoing data, we can obtain the final value of torsion for each weight. Since the writer expects to obtain more detailed data for ice by further experiments, he will be, for the present, satisfied by finding the final positions by graphical extrapolation. The relation between the torsion and the applied force, thus found, is given in Figure 5. This curve is not the same as the curve in Figure 1, where the mode of application of force was different from the present case, as were also the dimensions of the test piece.

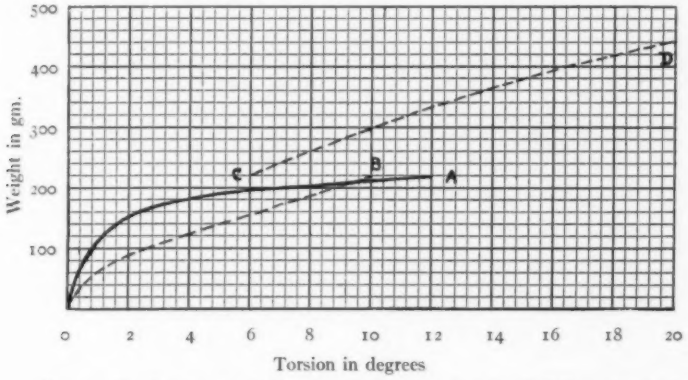

FIG. 5.—Torsion curves obtained from Figures 4 and 6. Full line: for the bar with crystals transverse to its longer dimension. Broken line: for the bar with crystals parallel to its axis.

Similar observations were tried on a test piece with crystals parallel to the length. It was 20.95 cm. long and 1.93 cm. in diameter (Fig. 6). During this test, it was noticed that the twisting curve for 308 gm. was very close to that for 220 gm. When repeated with 220 gm. once more, the deviation curve was found to be much lower than the former curve for the same amount of force. This fact suggests that ice shows the phenomena of elastic fatigue.[1] It was not learned whether this occurred after repetition of small deformations or after deformation of certain amount. It seems likely that this phenomena appears rather abruptly instead of gradually.

[1] Poynting and Thomson, *Properties of Matter*, p. 57.

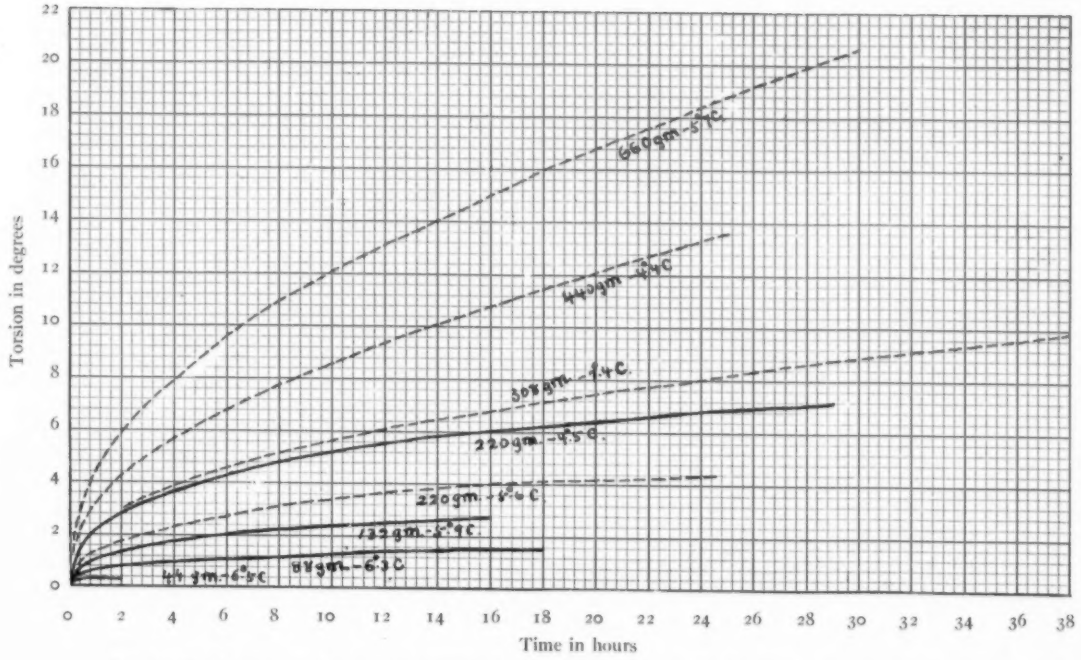

FIG. 6.—Torsion curves, by constant forces, of a circular ice bar, 20.95 cm. long and 1.93 cm. in diameter with crystals parallel to its axis.

The torsion curve for the case with crystals parallel to the axis of the test piece was also obtained as on the other case and is shown in Figure 5 by the broken line. Since the test specimens for these two cases were of nearly the same dimensions, we can compare the two curves with each other and consider the relative ease of yielding to torsional stress. As long as the deforming force remains less than 200 gm. the deformation for the former case is much smaller than for the latter. After that the curve becomes very flat showing that the specimen begins to yield readily. The curve for the latter rod shows a discrepancy between the points *B* and *C*. After that it still keeps on its steepness, becoming flatter after the point *D*, though this is not shown in the figure. Attention must be called to the fact that the observations for the former rod were made after it had been used repeatedly for other tests. It is, therefore, probable that this rod was already affected by the elastic fatigue when the present series of observations began. Lacking the knowledge how far this is the case, it is not safe to compare the curves for weights of less than 200 gm. When the weight is greater than this, it seems quite probable that the former rod, in which the constituent crystals are lying transverse to it, is twisted more easily than the latter, in which they are parallel to the length of the rod.

TORSION BY INCREASING FORCE

Whatever may be the fundamental property of ice by which the glacial motion takes place, the rate of accumulation of snow must be one of the most important factors influencing that motion. The corresponding study in the laboratory should be to find the relation between the deformation and different rates of increase of deforming force. For this purpose, a series of observations has been made with the same two test rods of different orientations of crystals as before.

The observed deformations of the first rod, where the crystals were arranged transverse to the rod, are shown in Figure 7. Since the deformation of a plastic body under constant force increases with time, it is clear that when the force increases slowly, the deformation for the same amount of force will be greater than when the force is increased rapidly. This relation is clearly shown in the

figure, the curve being steeper when the force is increased more rapidly. One curve, when the force was increased by the rate of 1.76 gm. per minute, is exceptional and steeper than the curves for the rates of 4.4 gm. and 2.2 gm. per minute as is shown by the broken line. The other curve for the same rate, which is not given in the figure, was very close to and slightly steeper than the curve for the rate of 2.2 gm. per minute. Since these two curves

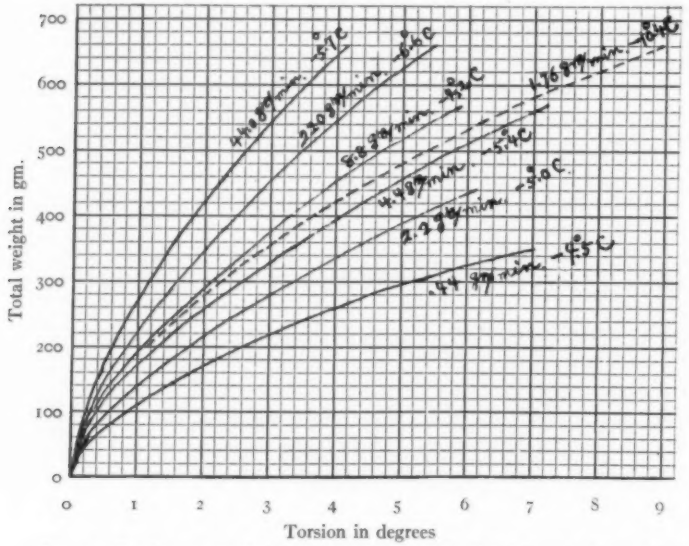

FIG. 7.—Torsion curves, by increasing force, of the first bar used for torsion by constant force.

were obtained by the last observations of the present series, the foregoing fact may be considered as the result of elastic fatigue. The difference between these two curves for the same rate of increase of force may be due to the difference of temperature which was respectively $-10°.4$ C. for the steeper and $-4°.6$ C. for the flatter.

Similar curves, though less numerous, were obtained with the second rod, in which the crystals were parallel to the length of the rod. These are shown in Figure 8. Here the deformation for

the rate of 1.76 gm. per minute was observed before it was used for the series of experiments on torsion by constant force in which the effect of elastic fatigue, as previously stated, was observed in pronounced form. The other two curves were obtained after that, and hence it is possible that the flatness of the first curve compared to the curve for .88 gm. per minute, which should not be the case, may be due to fatigue.

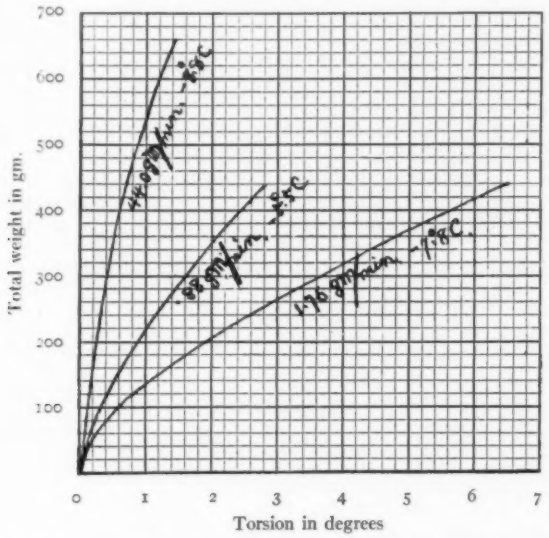

FIG. 8.—Torsion curves, by increasing force, of the second bar used for torsion by constant force.

The curves in Figure 7 were obtained after the observations for the torsion by constant force. We have seen before that the test piece was already subjected to fatigue in that case, and consequently the present curves will be affected in the same way. As a very rough approximation, therefore, we may compare the curves for the rates of .88 gm. and 44.0 gm. per minute in Figure 8, assuming the effect of fatigue to be the same after it has abruptly appeared and also neglecting the effect of temperature, which did not differ very much. The former curves are so much steeper that this

approximation seems safe. This steepness of the former curves means that ice is more easily twisted when the constituent crystals are arranged transverse to the rod than when they are parallel to its axis.

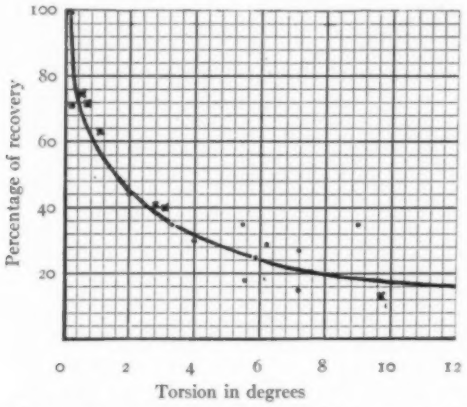

FIG. 9.—Recovery curve for the rod with crystals transverse to its longer dimension. Crosses for constant force and dots for increasing force.

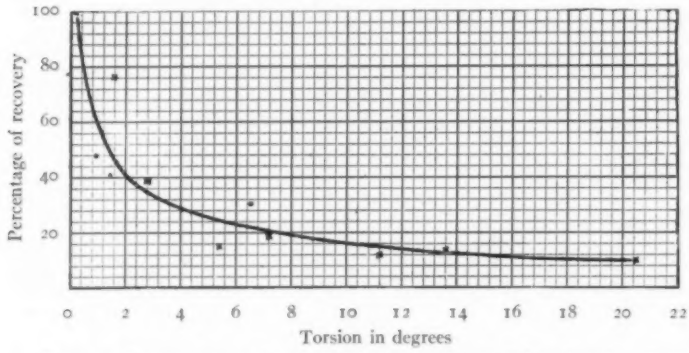

FIG. 10.—Recovery curve for the rod with crystals parallel to its axis. Crosses for constant force and dots for increasing force.

RECOVERY FROM DEFORMATION

While observing the deformations by constant force as well as by increasing force, the amount of return toward the original state

after removal of the force was observed in each case. Beside the amount of torsion, the recovery will depend upon various other conditions, like the temperature, mode of applying the force, and its duration. These values are given in the following tables:

CONSTANT FORCE. CRYSTALS TRANSVERSE

Temperature	Weight	Duration	Deformation	Recovery	Percentage
−9°0C.....	22 gm.	0^h15^m	0° 4′	0° 4′	100
−9.6.....	44	1 0	0 8	0 8	100
−9.0.....	66	1 0	0 14	0 14	71
−9.5.....	88	2 0	0 32	0 24	75
−9.0.....	110	3 5	0 36	0 26	72
−9.0.....	132	3 45	1 5	0 41	63
−8.8.....	154	6 20	2 50	1 2	41
−8.1.....	176	10 39	3 2	1 12	40
−8.7.....	229	37 20	9 44	1 18	13

CONSTANT FORCE. CRYSTALS PARALLEL

Temperature	Weight	Duration	Deformation	Recovery	Percentage
−9°2C.....	5 gm.	0^h55^m	0° 44′	0° 4′	100
−8.6.....	44	1 45	0 10	0 10	100
−6.3.....	88	15 10	1 38	1 15	77
−5.8.....	132	15 0	2 48	1 6	39
−7.3.....	229	29 30	7 12	1 21	19
−5.7.....	220	12 40	5 24	0 48	15
−7.1.....	308	48 0	11 11	1 16	12
−4.4.....	440	13 0	13 38	1 56	14
−5.7.....	660	18 0	20 36	2 8	10

INCREASING FORCE. CRYSTALS TRANSVERSE

Temperature	Increased Rate	Duration	Final Weight	Deformation	Recovery	Percentage
− 4°5C.....	.44 gm./min.	13^h20^m	352 gm.	7° 12′	1° 24′	19
− 4.7.....	.88	5 0	264	3 20	1 10	35
− 4.6.....	1.76	2 5	222	2 2	0 54	44
−10.4.....	1.76	6 15	660	8 58	2 46	31
− 5.0.....	2.2	3 20	440	6 8	1 46	29
− 5.4.....	4.4	2 10	572	7 12	1 58	27
− 6.3.....	8.8	1 5	572	5 28	1 42	31
− 4.3.....	8.8	1 5	572	5 56	1 30	25
− 6.0.....	22.0	0 30	660	5 30	0 58	18
− 5.7.....	44.0	0 15	660	4 0	1 12	30

INCREASING FORCE. CRYSTALS PARALLEL

Temperature	Increased Rate	Duration	Final Weight	Deformation	Recovery	Percentage
− 7°8C.....	.88 gm./min.	3^h35^m	189 gm.	0° 57′	0° 25′	44
− 5.5.....	1.76	4 10	440	6 30	2 0	31
− 9.0.....	44.0	0 15	660	1 27	0 36	41

The amount of recovery in percentage of the deformation is shown in Figures 9 and 10. For small forces the recovery is complete. As the amount of force which has been used increases the percentage of recovery decreases rapidly until the formation amounts to about four degrees. After this its decrease becomes slower and it approaches gradually to the zero line. Thus it is seen that the transition from the stage of nearly perfect elasticity to that of partial elasticity takes place very slowly in the cases both when the torsion is parallel to the optic axis of the constituent crystals and when it is parallel to the basal planes.

BENDING EXPERIMENTS

The observations on torsion of ice just presented have suggested that an aggregate of parallel crystals of ice is more easily deformed by a shearing force parallel to the axes of the constituent crystals than parallel to their basal sections. We have also seen that Young's modulus, or proportionate resistance to elongation which is generally determined by the method of bending, is greatest when the deforming force bending the test bar acts parallel to the basal sections of the constituent parallel crystals. The next step was to test the matter further by observing the behavior of bars of differently orientated crystals when bent beyond the limit of elasticity. It was desirable to try the experiment with bars of different sizes compared to the constituent crystals. But the temperature of laboratory was not favorable for the use of larger bars with larger deforming force. Bars of moderate size with rectangular cross-sections were therefore prepared with different orientations of crystals. Each bar was supported at both ends by knife-edges and a weight of 100 gm. was hung from the middle point. The bending was measured by the lowering of this central portion. In Figure 11 some of the results of these observations are given, the data for the bars being given in the following table:

Bar	Optic Axes	Span	Breadth	Thickness	Temperature
a.....	Horizontal	9.0 cm.	.90 cm.	.60 cm.	−5°8 C. to −2°0 C.
c.....	Parallel	9.0	.90	60	−5.8 to −3.0
b.....	Vertical	9.0	.60	.58	−2.6 to −0.2
c.....	Parallel	9.0	.60	.58	−2.6 to 0.0

The first specimen bent much more easily than the second and broke at the point *A* in the figure. The same applies to the third and fourth specimens.

In another case, three test pieces, each 0.80 cm. wide and 0.50 cm. thick, were supported with an 8.0 cm. span between the supports. The lowering of the central part by 100 gm. in the first eight hours was 2.68 cm., 0.2 cm., and 1.22 cm. respectively for the different orientations *a*, *b*, and *c*. A part of the weight

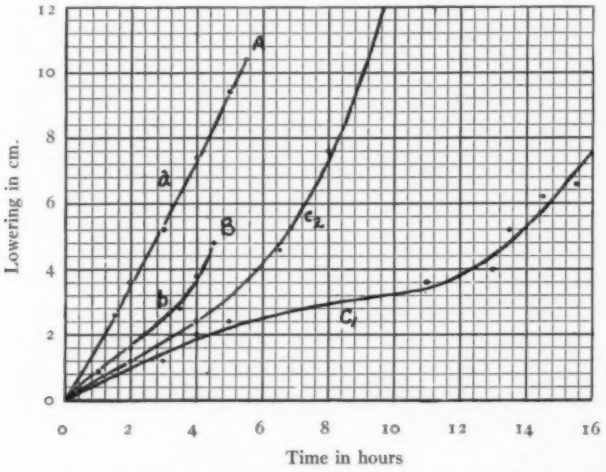

FIG. 11.—Relative ease of bending of ice bars with different orientations of crystals.

hanging from the second bar was found supported from beneath by accident so that its bending is not comparable with others. The temperature during this observation ranged from $-5°.0$ to $-2°.7$ C.

It is clear from these observations that ice bars with their constituent crystals perpendicular to the length, bend and break more easily than the bar with crystals parallel to the length. In the case of observation for the bars *b* and *c*, the temperature became so high that the bar suffered from pressure melting at the

knife-edges, thus preventing free movement. On account of this, the result may not be much relied upon and consequently the relative ease of bending of the bars *a* and *b* is not determined. The other observation stated above also failed to give any idea about this.

As to the nature of deformation of ice comprising of an aggregate of crystals, many authors have claimed that it depends upon the behavior of a single crystal. It is stated that in a case of bending of an ice bar consisting of several crystals, most of the bending had taken place in one of the crystals lying with its crystal axis nearly horizontal and approximately parallel to the length of the bar.[1] This is understood to mean that in such a case movement along the gliding planes of an ice crystal parallel to its basal plane is more effective than movements along the contact surfaces of adjacent crystals. If this theory is applicable to the present case the third bar in which the gliding planes were transverse to the long dimension should bend most easily. But quite to the contrary, bar of orientation *c*, instead of bending most readily, suffered the least bending of any of the three types of orientation.

As to the mechanism of bending within the limit of perfect elasticity it is generally understood by physicists that bending of a bar is caused by shortening of the concave side and elongation of the convex. When bending becomes larger than this, it is difficult to solve the case as a simple mechanical problem. It is probable in such a case that the portion near the point of application of force is subjected to bending, while the other parts are elongated with some degree of sliding at the knife-edges. The mechanism at the bending-point will depend upon the structure of the material. If it is deformable more easily in one direction than in another the problem becomes complicated. The resulting deformation in such a case will be the combination of that effect with the result of shortening and elongation phenomena. The experimental fact above described that bars of type *c* bend less easily than the others suggests that contact surfaces between adjacent crystals play greater rôle than the so-called gliding planes parallel to the basal plane.

[1] R. S. Tarr and J. L. Rich, *Zeits. f. Glets.*, Vol. VI (1911), p. 236.

MICROSCOPIC EVIDENCES

The theory that an ice crystal is composed of thin laminae parallel to its basal plane gives rise to the conclusion that when the crystal is bent by force perpendicular to its optic axis, it will show simultaneous extinction at the bent and unbent portions under the petrographic microscope.[1] Tarr and Rich[2] have described the case in which this optical property of the bent bar was not changed, as well as when it was changed. In the latter case the original optic axis was either parallel or perpendicular to the length of the bar, and if we assume the latter as the case, it is in contradiction to the idea that movement along the gliding planes controlled the bending.

The present writer examined the bent parts of an ice bar and the results were very suggestive, showing facts which seem not to agree with former ideas. A bar of ice with crystals parallel to its length was bent under certain stress. When the bent portion was thinned down and examined under the microscope with the Nicols crossed, it clearly showed an extinction strip across the bar, which moved along the bent portion as the stage was turned. Wanting to be sure about this, the writer asked Professor R. T. Chamberlin to see it and he recognized the same fact with certainty. The test piece in this case consisted of one main crystal with small portions of other crystals on either side. The same fact was observed in one more case but with the oncoming of warm weather these two were the only trials which it was possible to undertake in the present investigation.

Examinations without crossed Nicols revealed another important fact. The test specimen consisted of parallel crystals whose optical axes were horizontally transverse to the length. The bent portion was examined under microscope so as to see the side of the bar, i.e., the basal planes of the crystals. In the field of the microscope, it was found that faint but distinct straight lines nearly parallel to each other had developed on the sections of the crystals. The boundaries of the crystals were zigzag and sometimes the straight lines developed in the crystals were observed to

[1] R. S. Tarr and O. D. von Engeln, *Zeits. f. Glets.*, Vol. IX (1915), p. 111.

[2] R. S. Tarr and J. L. Rich, *Zeits. f. Glets.*, Vol. VI (1911–12), p. 235.

start from the angular points of these zigzag boundaries. The direction of the parallel straight lines was not the same in different crystals. Sometimes apparently two systems of these straight lines developed in one crystal, nearly perpendicular to each other. When the unbent portion of the same bar was examined in the same way, the crystals were found to be bounded by very smooth boundaries and no straight lines in their sections were visible. In another case, the same crystals were identified before and after bending took place. The same contrast of the disturbed and undisturbed crystals was observable in this case.

At the time of these observations, the equipment for petrographic photography was not available for the writer. He was obliged to content himself with very careful sketches of these phenomena as they appeared to him. These are shown in Figures 12 and 13. Since these figures represent the sections nearly parallel to the base, the straight lines in the sections must be considered to show the development of a system or two of parallel planes parallel to the optic axis. Uniform extinction was generally observed throughout each individual crystal, but in some crystals portions divided by the straight lines showed slight difference in extinction.

Bearing upon the question of straight lines in the section, Tarr and Rich[1] describe one case in which phenomenon of the sort were observed. They regarded it as notable, however, that this was the only one of their experiments in which bending took place by shearing. Their experiment was about the bending of a single crystal of glacier ice whose optic axis was parallel to the supporting edge. In the present investigation, the same phenomena was observed whenever the constituent crystals were perpendicular to the bending plane. It has already been stated that deformation either by torsional, or by bending, stress took place least easily when the force was applied parallel to the basal section of the constituent crystals. This was thought to suggest that in the deformation of an aggregate of parallel crystals, the contact surfaces between adjacent crystals probably have played an important

[1] R. S. Tarr and J. L. Rich, *Zeits. f. Glets.*, Vol. VI (1911–12), p. 243.

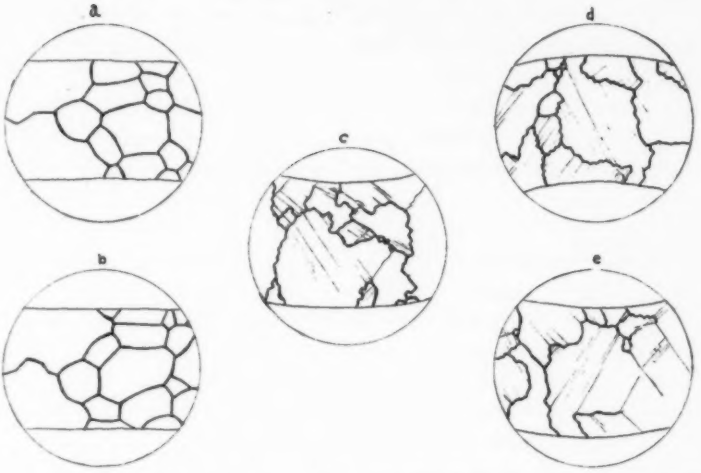

FIG. 12.—Microscopic appearances of ice crystals after bending. *a* and *b:* unbent portions. *c*, *d*, and *e:* bent portions.

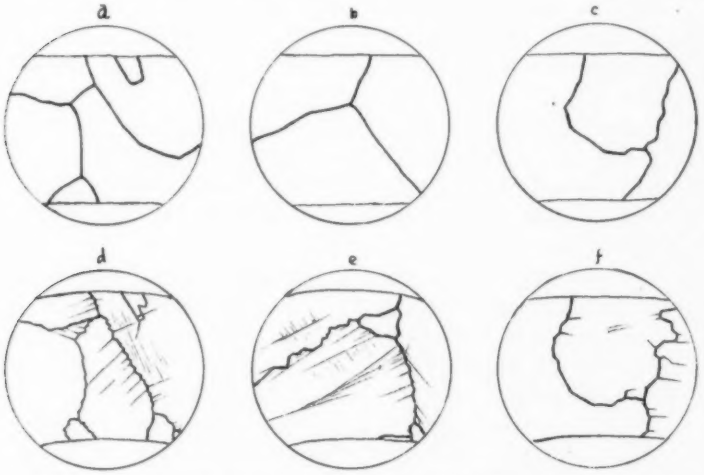

FIG. 13.—Microscopic appearances of ice crystals before and after bending. *a*, *b*, and *c:* before bending. *d*, *e*, and *f:* after bending.

part if the idea of McConnell and Mügge is correct. The development of the planes parallel to the optic axis suggests that an ice crystal has a greater tendency toward deformation parallel to the optic axis than perpendicular to it. To what degree this property of an ice crystal and the contact surfaces are concerned in the deformation of ice is to be decided by further study.

CONCLUSIONS

In some specimens of ice a sharply defined elastic limit was noted, though in other cases it was not so clearly shown.

The modulus of rigidity of ice, when the crystals are perpendicular to the axis of the test piece, is very small compared to that of metals, and is about 2×10^6 c.g.s. There is a slight indication that it is greater when the shearing is parallel to the base of the constituent crystals than when it is perpendicular.

The Young's modulus is also very small compared to that of metals. It is largest when the crystals are parallel to the length of the test piece, and has the numerical value about 20×10^6 c.g.s.

Elastic fatigue was marked after repeated torsion. On account of the fact that it was often necessary to use certain bars in successive experiments during which they suffered from different amounts of fatigue, it was difficult to compare the results bearing on ice bars with crystals parallel and perpendicular to the length of the test piece. Still there were some indications that beyond the limit of elasticity the former orientation was stronger than the latter against torsion. In the case of bending experiments, this was clearly shown.

The torsional deformations both by constant and by increasing forces were observed and the result is shown by curves, though no mathematical conclusions were made. The recovery curves showed that the observation was approaching the stage where no recovery would take place after removal of the force.

When an ice bar with crystals parallel to its length was bent, the bent portion showed the change of optical character, the extinction swinging around the curve. In each crystal when the bent specimen consisted of parallel crystals horizontally across it, parallel straight lines were observed.

These facts seem to show that gliding planes parallel to the base of each crystal are not the controlling factor in the deformation of ice and probably are not even an important factor. But instead, adjustments along the contact surfaces of adjacent crystals and perhaps the development of planes of weakness in the constituent crystals parallel to their long axis seem more effective in the process of deformation.

A TEST OF THE FELDSPAR METHOD FOR THE DETERMINATION OF THE ORIGIN OF METAMORPHIC ROCKS

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1. *Purpose of paper.*—That feldspars may serve as indicators of the original character of gneisses and schists is dependent upon the narrow range of composition possessed by the plagioclase feldspars of igneous rocks. Thus more than one kind of plagioclase feldspar is rarely found in an igneous rock except in certain zonal intergrowths or in some porphyries where the feldspars forming the phenocrysts may be of slightly different composition from those of the groundmass.

In sediments, except in rare cases where they are derived from rocks having feldspars with a narrow range of composition, the limited feldspar composition found in igneous rocks is not to be expected. Usually sediments are derived from many sources and consequently mixtures of all kinds of feldspars are possible. It would seem reasonable then to believe that gneisses and schists with a narrow range of feldspar composition are probably igneous in origin, whereas metamorphic rocks with several varieties of feldspar are very likely of sedimentary origin. This belief, however, rests on the fundamental assumption that the feldspar range typical of sediments does not radically change during anamorphism of these sediments. It is readily seen that if such a change does take place it vitiates any conclusions which might be reached. Similarly, if in the anamorphism of igneous rocks a radical change in the original feldspar composition results, this also would militate against the efficacy of the feldspar method.

That feldspars undergo alteration in various stages of the metamorphic cycle is generally recognized. It is not known that this

alteration tends to produce feldspars of varied composition from one particular feldspar, nor conversely to change a wide feldspar range into a narrow one.

The purpose of the work of this thesis was to determine the efficacy and validity of the hypothesis as above stated, namely, that metamorphic rocks having a narrow range of feldspar composition are probably igneous in origin, whereas those having a wide range of feldspar composition are more likely of sedimentary origin. To test the validity of this hypothesis it was first necessary to get some idea as to the abundance of feldspars in various sediments and also to determine the range in composition of these feldspars. This involved a study of sediments both in the unconsolidated and consolidated form. It was then further necessary to study metamorphic rocks of known sedimentary and igneous origin in order to note whether the feldspar composition was such as would have characterized the original sedimentary or igneous equivalent. The methods used in this study and the results obtained are presented in this paper.

The writer wishes to acknowledge his indebtedness to Dr. Edward Steidtmann, of the University of Wisconsin, for suggesting the fundamental idea upon which the feldspar method is based, and to Professors A. N. Winchell and C. K. Leith for suggestions and criticisms.

2. *Methods used to determine feldspars.*—In the determination of the feldspars two distinct methods were used depending upon the character of the material to be examined. Where thin sections were available and the rock was fairly coarse grained the Fouque method was found very serviceable.

When thin sections were not available and the material was so fine grained as not to be adapted to the Fouque method, the material was studied in powdered form and the feldspars determined by immersion in a series of liquids of known index. With the liquids either the Becke or inclined illumination method can be used. The determination of feldspars from rock powders in this manner is especially valuable in cases where the feldspars are partly altered, where the rock is fine grained, when the feldspar content is low, and for all unconsolidated sediments.

3. *The materials studied.*—In getting material together for study the attempt was made to make this selection one which would most thoroughly test the feldspar method. The mineralogic composition of unconsolidated and consolidated sediments as well as of metamorphic rocks of known origin was therefore determined. In order that the sediments might represent the breaking down of as many rock formations as possible, they were chosen so as to include a wide geographic and stratigraphic distribution. The aim was also to avoid limiting the material studied to any one particular realm of deposition. Beach sands as well as sands of glacial, eolion, and locustrine origin were therefore chosen. The consolidated sediments examined included arkoses, graywackes, tuffaceous sandstones, and shales. Since the purpose of studying the metamorphic rocks was to determine whether anamorphism causes any changes in the feldspar composition of the original rock, the gneiss and schists were selected which showed different kinds and degrees of change.

4. *Tabulation of results.*—The table on page 636 shows the results of the feldspar determinations for the various kinds of material studied.

5. *The relative abundance of feldspars in sediments.*—The data available are not sufficient to warrant a dogmatic statement as to whether certain feldspars are more abundant in sediments than others. The studies by the writer of a large number of sediments of different origin, as well as of wide geographic and stratigraphic distribution, suggest very strongly, however, that certain feldspars are very common in sediments, whereas others are quite rare. Orthoclase, microcline, and the acid plagioclases are much more frequently met with in sediments than the basic feldspars. Microcline seems to be more common than any of the others, so that a careful study of sands which appear to be entirely composed of quartz usually reveals a few grains of this feldspar. By referring to the accompanying diagram (Fig. 1) the relative abundance of the various plagioclase feldspars is strikingly brought out. This abundance of the feldspars mentioned indicates either that they are especially common in the rocks from which they were derived or that the basic plagioclases suffer much more rapid

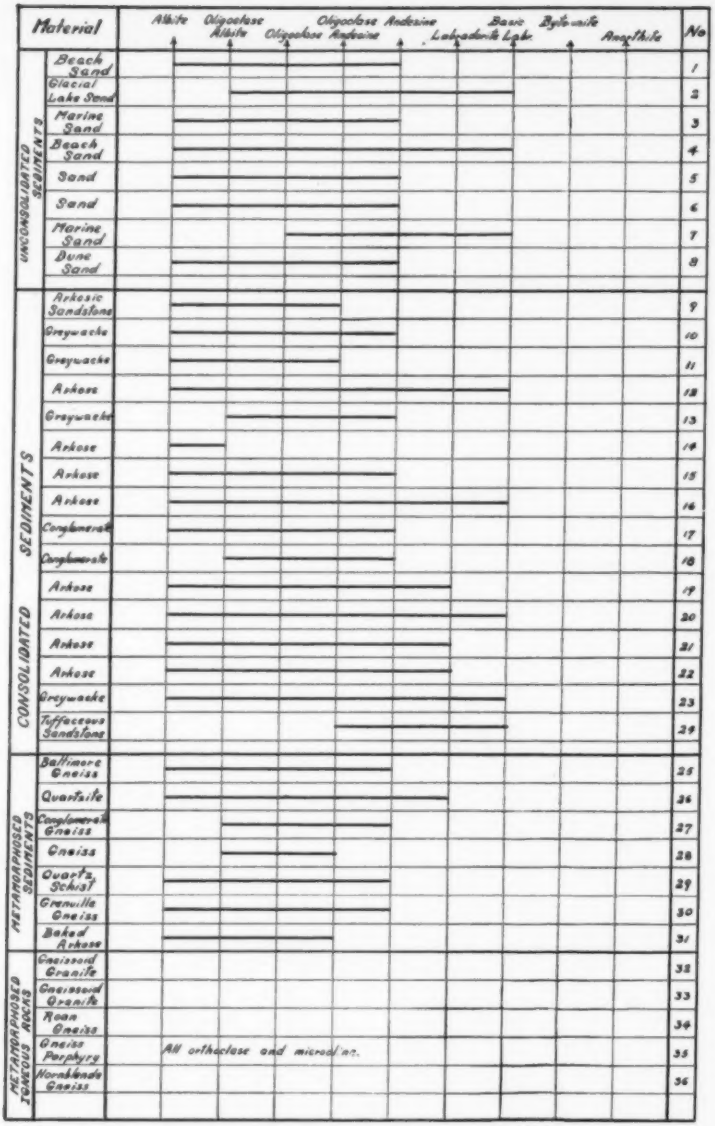

FIG. 1.—Diagram showing the range in feldspar composition for the various materials studied. The numbers refer to those on the accompanying tables where additional data are given. The solid black lines opposite the material indicated in the left-hand column show the range in feldspar composition for that material. Note the wide range of feldspars in the material of sedimentary origin as compared to that which is igneous in origin.

TABLE SHOWING DATA OBTAINED AS TO FELDSPAR COMPOSITION OF SEDIMENTS AND METAMORPHIC ROCKS OF KNOWN ORIGIN

	No.	Material	Locality	Feldspars Found	Method Used*	Remarks
Unconsolidated Sediments	1.....	Quartz Beach sand	South Carolina, Sullivans Island	Albite oligoclase, andesine, microcline, and orthoclase	B	Feldspar forms about 5 per cent of sand
	2.....	Glacial Lake sand	Middleton, Wisconsin	Oligoclase albite, oligoclase, andesine, labradorite, basic labradorite microcline	B	.....
	3.....	Marine sand Cambrian	South Point, Wisconsin	Albite, oligoclase, andesine, orthoclase, and microcline	B	Mineralogical composition of this sand = 36 per cent carbonate, 45 per cent quartz, 14 per cent feldspar, 5 per cent augite, hypersthene, apatite, zircon, garnet
	4.....	Beach sand. Largely derived from limestone but containing some glacial sand	Anticosti Island	Albite, oligoclase, andesine, basic labradorite, orthoclase, microcline	B	Mineralogical composition of this sand = 85 per cent carbonate, 8 per cent shale particles, 7 per cent quartz, feldspar and heavy residuals
	5.....	Sand. Contains reworked glacial material	From mouth of estuary between Goose and Lacroix Points, Anticosti Island	Albite, oligoclase, andesine, microcline, and orthoclase	B	Mineral composition—52 per cent c arbonate, 43 per cent quartz, and feldspar, 5 per cent heavy residuals. Bulk of sand of .124 mm. size
	6.....	Sand. Largely derived from limestone	From work in Chicotte formation Anticosti Island	Albite, andesine, microcline	B	Mineral composition = powder. 94 per cent carbonate, 4 per cent quartz, and feldspar; 2 per cent rock and mineral particles, 83 per cent of material coarser than .417 mm.

Consolidated Sediments	7.....	Marine sand Cambrian	Middleton, Wisconsin Interstratified with Oneota dolomite	Oligoclase, andesine, labradorite, basic labradorite, orthoclase and microcline	B	Mineral composition: 60 per cent quartz, 27.4 per cent carbonate, 11 per cent feldspar, 1.6 heavy residuals. Microcline abundant
	8.....	Dune sand	Golden Gate Park, California	Albite, oligoclase, andesine, microcline and orthoclase	B	.....
	9.....	Arkosic sandstone	Wausau, Wisconsin	Albite, oligoclase, oligoclase andesine, orthoclase and microcline	F	Plagioclase feldspars abundant. Pre-Cambrian
	10.....	Graywacke	Wausau, Wisconsin	Albite, oligoclase albite andesine, orthoclase	F	Pre-Cambrian
	11.....	Graywacke	Wausau, Wisconsin	Albite, oligoclase, andesine oligoclase, orthoclase	F	Pre-Cambrian
	12.....	Arkose Jurassic Triassic	New Jersey	Albite, oligoclase, albite, andesine, basic labradorite, microcline	B	Rock is from the Newark series; interpreted as being of terrestrial origin
	13.....	Graywacke Huronian	Hurley, Wisconsin	Oligoclase albite, oligoclase, oligoclase andesine, orthoclase and microcline	F	Rock composed of quartz and feldspar chiefly. Rock particles also present
	14.....	Arkose (Brown sandstone)	Hummelstown, Pennsylvania	Albite, oligoclase albite, orthoclase and microcline	F	Rock is part of Newark Series, of Jurassic-Triassicage
	15.....	Arkose	Clinton Point, Wisconsin	Albite, oligoclase, albite, oligoclase andesine	F	Feldspar is considerably kaolinized

* The letters B and F under the column headed "Method Used" stand for Becke and Fouque.

TABLE SHOWING DATA OBTAINED AS TO FELDSPAR COMPOSITION OF SEDIMENTS AND METAMORPHIC ROCKS OF KNOWN ORIGIN—*continued*

	No.	Material	Locality	Feldspars Found	Method Used*	Remarks
Consolidated Sediments	16.....	Arkose	Whitehall, Montana	Albite, oligoclase albite, oligoclase, andesine, basic labradorite, orthoclase	F	Plagioclase is abundant. Rock is fine-grained conglomerate
	17.....	Conglomerate Huronian	Cobalt, Ontario	Albite, andesine, microcline and orthoclase	F	Plagioclase not abundant
	18.....	Conglomerate	Oconto Bay, Wisconsin	Oligoclase albite, andesine, orthoclase and microcline	F	Plagioclase not abundant
	19.....	Arkosic sandstone Keweenawan age	Ontonogan County, northern Michigan	Albite, andesine, labradorite, microcline and orthoclase	B	Labradorite least abundant of plagioclases
	20.....	Arkose	Devils Rock, Cobalt District, Ontario	Albite, oligoclase, andesine, basic labradorite, orthoclase and microcline	B	Orthoclase abundant. Huronian
	21.....	Mashed arkose	Portage, Minnesota	Albite, oligoclase, andesine, labradorite, orthoclase and microcline	B	Microcline abundant; some of feldspars partially recrystallized. Huronian
	22.....	Arkosic sandstone	Southeast of Houghton, Michigan	Albite, andesine, labradorite, microcline	B	Cambrian
	23.....	Graywacke	Grafton Center, New Hampshire	Albite, oligoclase, andesine, basic labradorite	B	.....
		Tuffaceous sandstone	Teslo, California	Oligoclase, andesine, labra-	B	.....

Metamorphic Sedimentary Rocks	24.....	Tuffaceous sandstone	Teslo, California	Oligoclase, andesine, labradorite	B	.....
	25.....	Baltimore gneiss	Baltimore, Maryland	Albite, andesine	B	.....
	26.....	Arkosic quartzite	Temiskaming, Ontario	Albite, andesine, labradorite, microcline, orthoclase	B	Huronian age
	27.....	Conglomerate gneiss	Mill River, Massachusetts	Oligoclase, albite andesine, orthoclase, microcline	B	Microcline abundant
	28.....	Gneiss	Tyringham, Massachusetts	Oligoclase albite, oligoclase andesine, microcline and orthoclase	F	Microcline abundant
	29.....	Quartz schist	Ramshorn District, Montana	Albite, oligoclase, andesine, orthoclase	F	.....
	30.....	Grenville gneiss	Near New York City	Albite, oligoclase, andesine	B	.....
	31.....	Baked arkose conglomerate	South Britain Connecticut	Albite, oligoclase, andesine	B	.....
Metamorphic Igneous Rocks	32.....	Gneissoid granite	Three Rivers, Massachusetts	Albite only	B	.....
	33.....	Gneissoid granite	Thomaston, Connecticut	Albite only	B	.....
	34.....	Roan gneiss	Northern Georgia	All andesine	B	.....
	35.....	Gneiss porphyry	Dame de Muse, Ardenned, Belgium	All above albite. Microcline and orthoclase abundant	B	.....
	36.....	Hornblende gneiss	Ilchester, Maryland	All andesine	B	.....

*The letters B and F under the column headed "Method Used" stand for Becke and Fouque.

decomposition. The latter seems the more reasonable conclusion since many of the sediments studied have had their origin in areas of basic igneous rocks. At Keweenaw Point for example the Keweenawan sediments show a very small amount of the basic feldspars as compared to the acid varieties and yet the sediments have been largely derived from rocks of a decidedly basic character and from rocks in which basic feldspars are known to be very common. It is also generally recognized that the calcic feldspars are more readily decomposed than the more alkaline varieties. Iddings states that

> The alkalcic feldspars are not attacked by hydrochloric acid. The more calcic feldspars are decomposed by the acid in proportion to their content of calcium. Thus oligoclase and andesine are not attacked, labradorite is slightly acted upon, bytownite and anorthite are decomposed with the separation of gelatinous silica. In the rocks the more calcic feldspars are more readily decomposed than the more alkalcic feldspars in general.[1]

Feldspars are much more common in sediments than has generally been supposed. A large number of "sandstones" and "quartz" sands were in many cases found to have a considerable percentage of feldspar. Sands with a 5 per cent content of feldspar are not at all uncommon, while certain glacial and marine beach sands may contain feldspar up to 25 per cent.

6. *Feldspar range of rocks studied.*—It was desired to determine, by the work pursued in connection with this thesis, just what range in feldspar composition can be expected in sediments, and further to ascertain whether, during anamorphism, there is any change in the feldspar composition of the original igneous or sedimentary equivalent. The results obtained show that almost any combination of the various feldspars can be found in sedimentary rocks. Of the twenty-four samples studied, these samples including unconsolidated and consolidated sediments, twenty-three showed a range in feldspar composition from albite to andesine. Labradorite was found in eleven of the samples, while anorthite, due undoubtedly largely to its ready solubility as well as comparative rarity was not noted in any of the samples studied. As was expected glacial and marine beach sands show a very large range

[1] J. P. Iddings, *Rock Minerals*, p. 204.

in feldspar composition. Studies of metamorphic rocks of known igneous and sedimentary origin showed that the former retained their limited feldspar composition, whereas the metamorphic-sedimentary rocks included feldspar combinations such as would characterize the original sedimentary rock. The conclusion, as based upon the work done, is that there is no decided change, during anamorphism, of the feldspar composition possessed by the original unmetamorphosed material.

7. *The usefulness of the feldspar method as compared with the present criteria used in the determination of the origin of metamorphic rocks.*—The present criteria which are used to determine the igneous or sedimentary origin of metamorphic rocks are dependent upon field relations, together with chemical and mineralogical composition. Field evidence consists chiefly in tracing metamorphic rocks into the less altered igneous or sedimentary equivalents. Thus a basalt has often been observed to grade into a chlorite or micaceous schist. Similarly banded gneisses are often associated with and grade into granites. Chemical evidence suggestive of a sedimentary origin consists, according to Bastin[1] "of a dominance of magnesia over lime, potash over soda, excess of alumina and high silica. If the chemical composition is essentially that of an igneous rock this fact favors igneous origin." Mineralogical evidence favoring a sedimentary origin consists of a high content of quartz as does also an abundant development of aluminum silicate minerals. The presence of graphite probably denotes a sedimentary rather than an igneous origin.[2] Rounded grains of such minerals as garnet, sphene, and especially zircon have been taken as evidence of sedimentary origin. These minerals are especially resistant to weathering and will remain after the other minerals have been completely altered.

The plagioclase feldspar method is an addition to our mineralogical criteria. The results obtained prove the feldspar method to be a valid and reliable method for the determination of the

[1] Edson S. Bastin, "Chemical Composition as a Criterion in Identifying Metamorphosed Sediments," *Jour. Geol.*, XVII (1909), p. 472.

[2] J. D. Trueman, "The Value of Certain Criteria for the Determination of the Origin of the Foliated Crystalline Rocks," *Jour. Geol.*, XX (1912), pp. 228–58, 300–15.

metamorphic rocks to which it is applicable, and this means any rock containing recognizable feldspar constituents. The studies show that metamorphic rocks in general, except where they have suffered alteration due to ordinary weathering or hydrothermal alteration, contain such constituents. Where hydrothermal alteration has been effective, as in the proximity of the intrusive porphyries of the west, some other criteria must generally be resorted to. Even here, however, the alteration is not likely to have proceeded far from the main intrusive, so that by following a formation into its unweathered portion, recognizable feldspars may often be found. The feldspar method is to be preferred to the heavy residual or "zircon" criterion. The theory upon which the heavy residual method is based is undoubtedly a valid one, yet the studies of a large number of sediments show that any interpretations as to the origin of metamorphic rocks which are based upon its use, cannot be but uncertain. In the examination of marine beach sands from South Carolina and Anticosti Island, crystals of zircon and titanite were found which retained perfectly their crystal outline. Dr. W. H. Twenhofel reports similar results from a study of coral beach sands from the Hawaiian Islands. Such a sediment after conversion to a metamorphic rock would, on the basis of the zircon method, have been interpreted as suggestive of igneous origin. It must be borne in mind, however, that of all the criteria at present available for the determination of the origin of schists and gneisses, the use of field relations, where possible, is by far the most conclusive. Chemical and mineralogical criteria must therefore be subordinated to it. On the basis of practical usefulness and reliability the feldspar criterion should supply a valuable addition to our present laboratory methods.

SUMMARIES OF PRE-CAMBRIAN LITERATURE OF NORTH AMERICA

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II. ONTARIO

In the region northeast of Lake Huron, the pre-Cambrian rocks according to Collins and others show one conspicuous unconformity. The rocks beneath this unconformity comprise a series of quartzites and other clastic sediments, the Timiskaming series, etc., intruded by granitic rocks. Unconformably beneath these sediments is an older series, the Keewatin, including basic flows, some acid extrusives, iron formations, dolomites, etc. The Keewatin is intruded by the Laurentian granites and gneisses.

Above the conspicuous unconformity are two series of slightly metamorphosed dominantly clastic sediments separated by an inconspicuous unconformity. The lower one, the Bruce series, locally contains tillites. The upper series is generally known as the Cobalt series. At Killarney on the north shore of Lake Huron, Collins has found that the Bruce and possibly the Cobalt series are intruded by the Killarney granite and in this locality they assume many of the characteristics of the older series, the Timiskaming. The youngest pre-Cambrian rocks are Keweenawan, basic dikes and sills.

Northwest of Lake Superior, Lawson has restudied the Rainy Lake and Steeprock Lake districts. Greenstones and other rocks typical of the Keewatin are widely exposed in this region. Beneath them are acid schists called Coutchiching by Lawson. Unconformably above the Keewatin in the vicinity of Rainy Lake are a series of conglomerates and slates called the Seine series by Lawson. In the Steeprock Lake district, the Steeprock Lake series lies unconformably between the Keewatin and Seine series. The Steeprock Lake series, besides clastic sediments, comprises fossil-bearing dolomites.

The youngest rocks of the region are basic dikes classed as Keweenawan.

Baker[1] classifies the pre-Cambrian rocks of the Kingston area in southeastern Ontario as follows:

Great unconformity
Keweenawan—Trap, diabase, and gabbro intrusives
Intrusive contact
Algoman—Coarse-grained granite and syenite intrusives with later pegmatites
Intrusive contact
Laurentian—Gray to pink, medium to fine-grained, granitic gneisses
Intrusive contact
Grenville—White, coarsely crystalline limestone with quartzite and rusty weathering gneisses.
Dark green to black gneisses—thoroughly impregnated with minute dikes of Laurentian granite, now also changed to gneiss.

As reported by E. L. Bruce,[2] the succession in the Cripple Creek Gold district located about twenty-five miles southwest of Porcupine, Ontario, is:

Glacial and Recent
Peat, unsorted and more or less sorted sands and clays
Unconformity
Post-Laurentian
Diabase dikes
Igneous contact
Laurentian
Gray granite—reddish gneissoid granite
Igneous contact
Keewatin
Greenstones, schists, diabase, and iron formation

The Kirkland Lake and Swastika[3] gold areas are located in the Timiskaming district, fifty miles north of Cobalt. The pre-Cambrian rocks are classified as follows:

Later dikes—Diabase
Intrusive contact

[1] M. B. Baker, "The Geology of Kingston (Ontario) and Vicinity," *Ontario Bur. Mines, 25th Ann. Rept.*, Vol. XXV, Part 3 (1916), pp. 1–36, 19 figs., map.

[2] E. L. Bruce, geologist, and W. R. Rogers, topographer, "Cripple Creek Gold Area, *Ontario Bur. Mines*, Vol. XXI (1912), Part I, pp. 256–65, 9 figs.

[3] A. G. Burrows and P. E. Hopkins, "The Kirkland Lake and Swastika Gold Areas, *Ontario Bur. Mines, 23d Ann. Rept.*, Vol. XXIII, Part II (1914), pp. 1–39.

Cobalt series—Nearly flat-lying conglomerate with bowlders of granite and syenite

Unconformity

Post Timiskaming intrusives—Granite, syenite, feldspar, porphyry, lamprophyre

Intrusive contact

Timiskaming series—Quartzite, graywacke, conglomerate with schistose derivatives. The conglomerates contain a variety of pebbles derived from the Keewatin

Keewatin—Greenstone (basalt andesite) diabase, quartz porphyry, feldspar porphyry, iron formation, dolomite

Burrows[1] maps the Matachewan Gold area on Montreal River in latitude 48. Below is the table of formations:

Animikean-Cobalt series—Conglomerate, quartzite, graywacke, slate

Unconformity

Algoman—Granite, syenite, and thin acid intrusives

Intrusive contact

Laurentian—Granite and gneiss

Keewatin—Greenstones, iron formation, some quartzite, conglomerate, etc.

Burrows[2] classifies the pre-Cambrian rocks of the Porcupine Gold area of Ontario as follows:

Keweenawan—Quartz diabase, olivine diabase

Intrusive contact

Algoman—Granite porphyry, feldspar porphyry

Intrusive contact

Pre-Algoman—Lamprophyre, serpentine quartz porphyry

Intrusive contact

Timiskaming series—A series of schistose conglomerates, interbanded slate and graywacke, quartzite "carbonate" rock

Unconformity

Keewatin—A couple of largely schistose basic to acid volcanics, agglomerates, ash rocks, iron formation, rusty weathering, "carbonate," diabase, serpentine, etc.

The gold occurs in quartz veins cutting the Keewatin and Timiskaming series and the pre-Keweenawan intrusives. They are believed to be related genetically to the Algoman intrusives.

[1] A. G. Burrows, "The Matachewan Gold Area," *Ontario Bur. Mines, Ann. Rept.*, Vol. XXVII (1918), Part I, pp. 215–40, maps and illustrations.

[2] A. G. Burrows and P. E. Hopkins, "The Porcupine Gold Area" (Third Report), *Ontario Bur. Mines, Ann. Rept.*, Vol. XXIV, Part III (1915), pp. 1–57, 44 figs. inclusive, maps; see also *ibid.* (Second Report), *Ontario Bur. Mines 21st Ann. Rept.*, Vol. XXI (1912), pp. 205–49, 37 figs.

The Whiskey Lake[1] area includes two unsubdivided townships, Nos. 137 and 138, in the third and fourth tier of townships north of Lake Huron. The pre-Cambrian rocks of the area are provisionally classified as:

Middle Huronian—Conglomerate and quartzite
Unconformity
Lower Huronian—Conglomerate, quartzite, slate, and limestone
Great unconformity
Sudbury series—Slate and probably quartzite, part of the greenstone
Unconformity
Keewatin—Most of the greenstone and green schist
Laurentian—Granite and syenite

Coleman[2] classifies the pre-Cambrian succession along the north shore of Lake Huron as follows:

Keweenawan—Basic volcanic eruptives and basic sills. Subordinate coarse, usually red sediments, probably indicating warm, dry climate
Animikie—Black slates, volcanic tuff, bowlder conglomerate
Huronian—Arkose and quartzite, shallow lake or sea deposits indicating cool climate. Bowlder conglomerate or tillite formed under glacial conditions
Sudburian—Pillow basic lava flows. Coarse sediments—conglomerates, bowlder beds, arkoses, quartzites derived mainly from the disintegration of granites
Grenville—Quartzites, schist, and impure calcareous sediments whose relation to the Keewatin is uncertain. Intrusion of granites
Keewatin—Basic eruptions and jaspititic iron formations

Coleman[3] classifies the pre-Cambrian rocks of the region north of Lake Huron extending from Point Mamainse to Wanapitie as follows:

Post-Laurentian
- Keweenawan
- Discordance
- Animikie
- Discordance
- Upper Huronian

Great discordance

Pre-Laurentian
- Sudbury series
- Great discordance
- Keewatin—Probably equal to the Grenville series

[1] A. P. Coleman, "The Whiskey Lake Area," *Ontario Bur. Mines, 22d Ann. Rept.*, Vol. XXII (1913), Part I, pp. 146–54, 5 figs.

[2] A. P. Coleman, "The Pre-Cambrian Rocks North of Lake Huron with Special Reference to the Sudbury Series," *Ontario Bur. Mines, Ann. Rept.*, Vol. XXIII (1914), Part I, pp. 204–36, map, 18 figs.

[3] A. P. Coleman, "The Sudbury Series and Its Bearing on Pre-Cambrian Classification," *Congrès Géologique International XII.* Session 1914.

The major divisions are based on the position of the various series with reference to a conspicuous unconformity and to certain granite batholiths. He recommends that this section be adopted as a standard for the Lake Superior region.

In 1915 Coleman[1] classified the rocks of the Canadian Shield to the northeast of Lake Huron as follows:

Late Proterozoic	Keweenawan (Mamainse and nickel eruptive)	
	Discordance	
	Upper Huronian	Typical Huronian
	Small discordance	Typical Huronian
	Lower Huronian	Typical Huronian
	Great discordance	
Early Proterozoic	(Laurentian granite and gneiss)	
	Eruptive contact	
	Sudburian—Timiskaming, Pontiac, etc.	
	Great discordance	
Archaeozoic	(Granite eruptive through lower series)	
	Eruptive contact	
	Keewatin and Grenville	

The important points of this classification are the recognition of two major unconformities in the succession and the naming of certain granites and gneisses which are intrusive into rocks younger than the Keewatin, as Laurentian. In his discussion following the classification, he substitutes the term Animikie for Upper Huronian. The term Sudburian for a series is recent in the general discussions of the stratigraphy of the Canadian Shield. This series, Coleman states, is typically developed in the Sudbury district, where it consists chiefly of quartzites, slates, and conglomerates, without limestones or dolomites, and with almost no carbon. These rocks are severely folded, but not intensely altered excepting near intrusives. Their deposition was followed by the extrusion of lava Sudburite, the effusive equivalent of Norite. Other probably Sudburian areas include portions of the region to the northeast of the Wahnapitae River, and the Timiskaming, Gowganda, Larder Lake districts, the area of the Pontiac series of Quebec, the Doré formation of the east shore of Lake Superior, and certain rocks of Heron Bay on the north shore of Lake Superior,

[1] A. P. Coleman, "The Proterozoic of the Canadian Shield and Its Problems," *Problems of American Geology* (1915), pp. 81–161.

the Nipigon area, the Onaman Iron Range, and the Seine River in the Rainy Lake district. The Sudbury series he regards as being partly a delta deposit laid down in a moist cool climate, but finds it strange that carbon is lacking. In the interval between Sudburian and Huronian time, the area was folded and eroded to a surface very much like that of the present Canadian Shield.

For the nature of the Lower Huronian, he refers to Logan's type section on the northeast coast of Lake Huron. Tillites are a characteristic constituent of the Huronian, but in addition it contains stratified deposits. Other Lower Huronian areas are found in the Larder Lake, Chibougama, and Steep Rock Lake districts. The Lower Huronian rocks have a marked unconformity at their base, but are in general less severely folded than the Sudbury series. At the start the climate of the period appears to have been cool and glacial. The existence of animals is suggested by the occurrence of limestone.

The Animikie he characterizes as a period of great submergence during which great quantities of iron compounds and black slates were deposited.

The Keweenawan of the Canadian Shield rests upon the eroded Animikie. It includes three series, of which the two lower are chiefly sedimentary, while the upper is largely volcanic. The sediments consist largely of sandstones and conglomerates, characterized by red color and absence of carbon. The volcanics are chiefly basic flows, but possibly include some felsites and porphyries. Dikes are common, but as yet no definite volcanic vents have been found. Other areas of the Canadian Shield probably containing Keweenawan are the Nastapoka and Manitaunick Islands, Central Labrador, and the south side of Hudson Straits, the regions of Lake Athabasca, Great Slave Lake, and the area between the east side of Great Bear Lake along the Copper Mine River northward to the Arctic Ocean. Deposition during Keweenawan time, according to Coleman, was chiefly on the land in a warm dry climate. He speculates as to the source of great quantities of lavas and relates the development of the Lake Nipigon, Sudbury, and Lake Superior basins to the collapse of the surface resulting from the extrusion of the lavas.

The base of the succession exposed in the Gowganda[1] district consists of Keewatin greenstones mostly of igneous origin associated with some iron formation. They are intruded by batholiths of Laurentian granite. Overlying the granites and greenstones with well-marked unconformity are Huronian sediments which are separated into two members by a faint unconformity. The lower group from 500 to 1,000 feet thick consists of conglomerates, arkose, graywacke, and slates, showing poor assortment, variable bedding, and till-like character in the coarse phases. Locally, the beds are associated with rhyolitic extrusions. The upper is a single quartzite formation 600 or more feet thick, ranging from arkose to pure, well-bedded quartzite.

Intruded into the preceding are Keweenawan diabase sills and dikes.

Selected areas between the original Huronian and the Cobalt and Sudbury districts were examined by Collins[2] with the view of correlation. The Bruce, Blind River, Whiskey Lake, Española, and Round Lake areas were selected, the widest gap between them being about 28 miles.

Collins recognizes two major stratigraphic divisions, the pre-Huronian and the Huronian. They are separated by the most conspicuous unconformity of the region, characterized by a strong basal conglomerate, great differences in structure, metamorphism, igneous intrusions, and general lithologic character of the two groups. The pre-Huronian consists of basic schists and gneisses mostly of igneous origin, granite batholiths of more than one period of intrusion and highly metamorphosed slates and quartzites. The pre-Huronian has not been completely subdivided into stratigraphic units and its various members have not been traced and correlated over the entire region.

The Huronian is separated into two units by an unconformity far less pronounced than the one at the base of the Huronian. Individual beds of both divisions have been traced successfully from district to district. The lower division, called the Bruce

[1] W. H. Collins, "The Geology of Gowganda Mining Division," *Canada Geol. Surv. Mem. No. 33* (1913), 121 pp., 4 pls., 5 figs.

[2] W. H. Collins, "The Huronian Formations of Timiskaming Region, Canada," *Canada Geol. Surv. Mus. Bull. No. 8* (1914), 27 pp., 2 maps, 1 fig., 1 pl.

series, consists of a thin basal conglomerate, white quartzites with interbedded, well-sorted conglomerates, an impure siliceous limestone, and some graywacke, whose maximum thickness is more than three thousand feet. The upper division, or Cobalt series, includes tillites, quartzites, graywackes, a few thin impure limestone beds and grades upward into pure quartzites. It has in part the characteristics of glacial till associated with stream and quiet-water deposits contemporaneous with glaciation. Locally it shows minor unconformities. The local terms, Bruce and Cobalt series, rather than Lower Huronian and Upper Huronian, are applied to these divisions because their full equivalence to these units in the original Huronian is regarded as doubtful.

Collins[1] advocates that a local classification of the pre-Cambrian rocks of the Timiskaming region be adopted and that their correlation with other districts be postponed until they are better known. He emphasizes the importance of the unconformity at the base of the Cobalt series as major plane of division. The various series are classified by him as pre-Huronian and Huronian. His classification follows:

Keweenawan	Diabase Sudbury norite	
	Intrusive contact	
	Whitewater series	Huronian
	Lorrain series	
	Local unconformity	
	Cobalt series	
	Great unconformity	
	Batholithic granite intrusive	
	Intrusive contact	
	Sudbury, Timiskaming, Fabre series	Pre-Huronian
	Unconformity	
	Granite intrusives	
	Keewatin group	

Collins[2] reports that hitherto unknown granites intrude the Bruce and probably the Cobalt series along the coast of Lake Huron.

[1] W. H. Collins, "A Classification of the Pre-Cambrian Formations in the Region East of Lake Superior," *Congrès Géologique International XII.* Session 1914, pp. 399–407.

[2] W. H. Collins, "The Age of the Killarney Granite (Ontario)," *Canada Geol. Surv. Mus. Bull. No. 22* (1916), 12 pp., 1 pl., 1 fig.

Collins[1] reports on the Onaping map area about fifty miles north of Sudbury. Following his former practice, he divides the pre-Cambrian rocks into Huronian and pre-Huronian. His table of pre-Cambrian formations follows:

Huronian—Keweenawan — Olivine diabase
Basic intrusives? — Quartz diabase
Quartz norite and intermediate varieties
Intrusive contact
Cobalt series—Upper white quartzite
Banded cherty quartzite
Lorrain quartzite
Gowganda formation:
Conglomerate
Graywacke
Limestone
Great unconformity
Pre-Huronian
Batholithic intrusives—Granite gneiss and its differentiates
Schist complex—Altered volcanic and intrusive rocks, iron formation, and other sediments

P. E. Hopkins[2] reports the succession in McArthur township of the Porcupine Gold Area as

Late intrusives—Diabase
Timiskaming?—Slates
Laurentian—Granites intrusive into Keewatin
Keewatin—Greenstone, serpentine, hornblende schists, porphyries, carbonates, and chert magnetite iron formation

Hopkins[3] reports on the Beatty-Munro Gold area in the Larder Lake mining division of Ontario, latitude 48° 30′, longitude 80° 15′. The rocks are all pre-Cambrian and are classified by Hopkins as follows:

Post-Timiskaming intrusives—Feldspar porphyry dikes
Intrusive contact
Diabase dikes and stocklike masses
Intrusive contact

[1] W. H. Collins, "Onaping Map Area (Ontario)," *Canada Geol. Surv. Mem., No. 95* (1917), 157 pp., 11 pls., 8 figs., 2 maps.

[2] P. E. Hopkins, "Notes on McArthur Township," *Ontario Bur. Mines, 21st Ann. Rept.*, Vol. XXI (1912), Part I, pp. 278–80, 2 figs.

[3] P. E. Hopkins, "The Beatty-Munro Gold Area (Ontario)," *Ontario Bur. Mines, Ann. Rept.*, Vol. XXIV (1915), Part I, pp. 171–84, 9 figs., 1 map.

Timiskaming series—slate, graywacke, quartzite conglomerate, and schistose derivatives

Igneous—Feldspar porphyry—relation to Timiskaming uncertain—intrudes Keewatin

Intrusive contact

Keewatin—Amygdaloidal and ellipsoidal basalt, diabase, serpentine, iron formation, and breccia, with metamorphosed equivalents

The gold occurs as free gold and as tellurides in quartz veins cutting Keewatin and Timiskaming rocks. The veins contain high-temperature minerals, viz., pyrrhotite and tourmaline.

Kindle and Burling[1] conclude that the escarpment of pre-Cambrian rocks which overlooks the plain of Paleozoic sediments north of the Ottawa and St. Lawrence rivers is due to normal faulting, the sediments being on the downthrow side. The facts which indicate this are: (*a*) the presence of Paleozoic outliers resting on a hummocky surface of pre-Cambrian rock north of the escarpment, the corresponding Paleozoic beds south of the escarpment being about seven hundred feet lower, (*b*) the extreme regularity of the escarpment, (*c*) the absence of Paleozoic re-entrants along the escarpment, (*d*) the lack of clastic material from the limestone adjacent to the pre-Cambrian rocks of the escarpment, (*e*) the dissimilarity of the escarpment features with other nearby pre-Cambrian borders where normal erosion has even yielded an escarpment of Paleozoic rocks, (*f*) the escarpment is at the northern border of a zone in which subsidence or normal faulting is characteristic.

Knight[2] finds the following succession of pre-Cambrian rocks in the Thessalon area on the north shore of Lake Huron to the west of Killarney. This is the original Huronian area of Logan.

Diabase dikes intersecting Nipissing

Keweenawan—Diabase

Intrusive contact

Nipissing diabase, similar to that at Cobalt and Gowganda—shows local gradations into pink micro pegmatite. Thessalon greenstone, a fine-grained basal sometimes amygdaloidal

Intrusive contact

[1] E. M. Kindle and L. D. Burling, "Structural Relations of the Pre-Cambrian and Paleozoic Rocks North of the Ottawa and St. Lawrence Valleys," *Canada Geol. Surv. Mus. Bull. No. 18* (1915), 23 pp., 2 pls., 6 figs.

[2] C. W. Knight, "The North Shore of Lake Huron," *Ontario Bur. Mines, Ann. Rept.*, Vol. XXIV (1915), Part I, pp. 216–41, 13 figs.

Animikean—1. Pink quartzite and arkose with thin beds of jasper conglomerate similar to Lorrain series at Cobalt
2. Slatelike graywacke—beautifully and thinly bedded
3. Conglomerate, graywacke, slatelike graywacke, quartzite, arkose

Great unconformity

Algoman—Granite, massive, and at times gneissoid

Knight[1] and others report on the Abitibi-Night Hawk Gold Area southeast of Cochrane on the Canadian National Railway. The succession includes Keewatin rocks consisting of basic pillow lavas, rhyolites, basalt, diabase, hornblende, and chlorite schists, which are overlain by slate graywacke, quartzite, conglomerate, and iron formation. These Keewatin rocks are intruded by diabase and gabbro, peridotite and pyroxenite, granite and other acid rocks, quartz diabase and olivine diabase dikes.

In 1911[2] A. C. Lawson restudied the Rainy Lake area which he had reported on in 1887. In 1887, Lawson reported that the pre-Cambrian rocks of this region were all Archean and that the succession from the bottom upward is as follows:

A series of clastic sediments metamorphosed to mica quartz schists and paragneisses called the Coutchiching. This series is conformably overlain by the Keewatin, consisting dominantly of amygdaloidal and ellipsodial greenstone lava flows, chloritic schists, and other basic rocks of a similar nature. The Coutchiching and Keewatin were intruded by batholithic masses of granite and granite gneisses and allied acid igneous rocks which caused the doming up of the rock into which they were injected.

The restudy of the Rainy Lake area by Lawson in 1911 was occasioned by the fact that the United States Geological Survey and the International Committee of 1898 did not accept Lawson's conclusion that there existed a Coutchiching series of rocks stratigraphically below the Keewatin. This dissent from the opinion of Lawson was based on field work by Van Hise in various parts

[1] C. W. Knight, A. G. Burrows, P. E. Hopkins, and A. L. Parsons, "Abitibi-Night Hawk Gold Area," *Ontario Bur. Mines, 28th Ann. Rept.* (1919), 84 pp., maps, and illustrations.

[2] "The Archean Geology of Rainy Lake," restudied by A. C. Lawson. *Canada Geol. Surv. Mem. No. 40* (1913), 111 pp., geological map in pocket, 9 pls., 1 fig.

of the Rainy Lake area, and in consequence of the examination of the Coutchiching series on the east end of Shoal Lake and along parts of the Seine River by the International Committee of 1898. The International Committee found that the so-called Coutchiching of Lawson on the east end of Shoal Lake consisted of conglomerates and other clastic sediments which unconformably overlie the Keewatin. They then concluded that all of the rocks mapped by Lawson as Coutchiching are not below the Keewatin.

In consequence of Lawson's restudy of 1911, he persists in classifying the rocks of the Rainy Lake area as Archean. He holds to this classification because he regards it as historically correct, having been, he claims, the usage of Logan in his map of the north shore of Lake Huron, and furthermore, he believes that the erosion interval which intervenes between the rocks of the Animikie series and those which precede it is the most conspicuous in the pre-Cambrian rocks of the Lake Superior region. He believes that the rocks on the far side of this erosion interval show greater metamorphism and more intense folding and a larger number of intrusions than those on the near side of this interval.

On re-examining the Coutchiching rocks on the east side of Shoal Lake, he finds that the conclusions of the International Committee are correct for this particular locality. He finds no evidence, however, to change his original conclusion regarding the Coutchiching which is wrapped around domes of intrusive granite and which dips under the Keewatin at a low angle in the region of Rice Bay and around Bear's Passage. Lawson's classification of the rocks of the Rainy Lake district follows.

Keweenawan—Diabase dikes	
Algoman	Granite, porphyritic, and syenite gneisses, and a basic facies of syenite
Huronian (Seine series)	Lamprophyric rocks
	Quartzite and slate, and schists
	Conglomerate
Laurentian—Granite and granite gneiss	
Archean Keewatin	Anorthite
	Hornblende gabbro
	Limestone (one seam)
	Greenstone, greenstone schists, felsite, sericite schist, ash beds, agglomerate, siliceous slates and schists, chert, mica schist
Coutchiching mica schist, paragneiss, and phyllite	

Lawson[1] classifies the pre-Cambrian rocks of Steeprock Lake, Ontario, as follows:

Algonkian	Keweenawan
	Erosion interval
	Animikie
	Eparchean interval
Archean	Granite gneiss, intrusive in the Seine series
	Irruptive contact
	Seine series
	Acute deformation and erosion interval
	Steeprock series
	Erosion interval
	Granite gneiss, intrusive in the Keewatin
	Irruptive contact
	Keewatin
	Coutchiching

The Steeprock series comprise interbedded sediments and irruptive rocks: dark-gray slate, agglomerate, greenstones and green schists, conglomerates, and limestone. Van Hise and Leith have correlated them as Lower Huronian.

Lawson describes certain radial calcareous and siliceous fossil structures of the limestones. The rays of these fossils extend to a roughly circular limit in section normal to the axis of the organism. In oblique sections, the border is usually elliptical. In some cases, they are cornucopia-shaped, the rays sometimes showing conical or elliptical septa. The rays vary from one to fifteen inches in length.

The paper is supplemented by descriptive notes on the fossils by W. D. Walcott.

Miller and Knight[2] discuss the metallogenetic epochs of Ontario. Most of the metal production comes from Keweenawan rocks and consists chiefly of silver, nickel, and copper in the order named. Next in importance are the Algoman gold-bearing granite intrusions which have been productive at Porcupine and many other places. The Keewatin has furnished a small tonnage of iron ore.

[1] A. C. Lawson, "The Geology of Steeprock Lake, Ontario," *Canada Dept. of Mines, Mem. No. 28* (1912), 23 pp., 2 pls.

[2] W. G. Miller and C. W. Knight, "Metallogenetic Epochs in the Pre-Cambrian of Ontario," *Ontario Bur. Mines, Ann. Rept.*, Vol. XXIV (1915), Part I, pp. 244–48, map; *Roy. Soc. Canada Trans.*, 3d Ser., Vol. IX (December, 1915), Section IV, pp. 241–49, 1 fig. (map).

Erosion has destroyed much ore. Some ore has been preserved by folding and faulting.

Miller and Knight's[1] classification of the pre-Cambrian of Ontario follows.

Keweenawan
Unconformity
Animikean
Includes rocks called Animikie heretofore, also Logan's type section, and the Cobalt and Ramsay Lake series. Minor unconformities occur within the Animikean
Great unconformity
(Algoman granite and gneiss
Igneous contact)
Laurentian of some authors, the Lorrain granite of Cobalt, and the Killarney granite of Lake Huron
Timiskamian
Includes sedimentaries of various localities heretofore called Huronian—also the Sudbury series of Coleman
Great unconformity
Same order as that at base of Animikie
(Laurentian granite and gneiss)
Igneous contact
Loganian { Grenville (sedimentary)
Keewatin (igneous)

The authors differ from Collins and Coleman in that the latter recognize a twofold division of the Animikean group. Other differences are largely a matter of names and emphasis on the relative importance of various features. Lawson, Coleman, and Collins emphasize the unconformity at the base of the Animikean and recognize two major groups. Miller and Knight stand alone in concluding that the Grenville of southeastern Ontario is in part interlayered, but largely above the Keewatin. Other authors are either less confident or express doubt as to the position of the Grenville.

Parsons[2] describes the productive iron deposits of the Michipicoten district.

[1] W. G. Miller and C. W. Knight, "Revision of Pre-Cambrian Classification in Ontario", *Jour. Geol.*, Vol. XXIII (1915), pp. 585–99.

[2] A. L. Parsons, "The Productive Area of the Michipicoten Iron Ranges (Ontario)," *Ontario Bur. Mines. Ann. Rept.*, Vol. XXIV (1915), Part I, pp. 185–213, 22 figs., 3 pls., maps.

Quirke[1] maps the Española area representing the eastward extension of the original Huronian. His classification of the pre-Cambrian follows.

Great unconformity
Huronian
  Keweenawan—Diabase injection
  Igneous contact
Cobalt series
  Gowganda formation—Massive slate
    Conglomerate member..... 400 feet
    Graywacke slate..... 400 feet
    Bedded conglomerate..... 650 feet
  Unconformity
Bruce series
  Serpent quartzite.....8,000 (?) feet
Española group
    Española limestone..... 25 feet
    Española graywacke..... 280 feet
    Bruce limestone..... 150 feet
  Slight unconformity
    Mississagi quartzite..... 4000 feet
  Great unconformity
Pre-Huronian
  Granite intrusions
  Igneous contact
    Basic intrusions
  Igneous contact
    Schistified sediments

Large-scale maps were made by Stansfield[2] of certain mica, apatite deposits in the townships of Hull and Buckingham of Ottawa Valley. The pre-Cambrian rocks underlying this area comprise:

Igneous intrusives
  c) Trap dykes
  b) Gabbro and pegmatites of the mineral deposits
  a) Older pegmatite veins
Grenville series
Ottawa gneiss

The Ottawa gneiss includes granite and syenite gneiss, crystalline limestones, quartzites, garnet-gneisses, sillimanite gneisses,

[1] Terence T. Quirke, "Española District, Ontario," *Canada Geol. Surv. Mem. No. 102* (1917), 75 pp. 6 pls., 8 figs., map.

[2] John Stansfield, "Certain Mica, Graphite, and Apatite Deposits of the Ottawa Valley," etc., *Canada Geol. Surv. Summ. Rept. 1911* (1912), pp. 280–85.

and certain unidentified gneisses have been listed as the constituents of the Grenville series in this area.

The Cobalt series[1] comprises a basal conglomerate, resting on a nearly level surface and an assemblage of arkose, quartzite, graywacke, and argillite. Gradations are found in both vertical and horizontal directions. The finer-grained bedded varieties are assigned to a lacustrine origin. The heterogeneous, angular conglomerates with "soled," and occasionally striated pebbles are believed to be glacial.

The Larder Lake[2] district located on the boundary between Ontario and Quebec, about thirty miles north of Lake Timiskaming shows the following succession of rocks, according to Morley E. Wilson:

Pleistocene and recent
  Gravel, sand, clay, and till
Huronian
  Conglomerate
  Graywacke
  Arkose
  Conglomerate
  Igneous contact
  Diabase, gabbro, syenite porphyry; the first two probably time equivalents of similar rocks in the Cobalt district
Laurentian
  Granite, gneiss, granodiorite, pegmatite, aplite
  Unconformity
Keewatin—Greenstones and greenstone schists largely of effusive origin, Larder slate and dolomite quartz porphyry, rhyolite and aplite intrusive into the preceding — Pontiac schists composed of biotite and quartz. Relation to Keewatin unknown
  Igneous contact

Wilson[3] argues against widespread correlations of pre-Cambrian rocks and urges that for the present local names should be given to series and formations.

[1] Morley E. Wilson, "The Cobalt Series: Its Character and Origin," *Jour. Geol.*, Vol. XXI (February-March, 1913), pp. 121–41, 3 figs.

[2] Morley E. Wilson, "Geology and Economic Resources, Larder Lake District, Ontario," *Canada Geol. Surv. Mem. No. 17* (1912), 62 pp., 11 pls., 5 figs., 2 maps.

[3] Morley E. Wilson, "Sub-Provincial Limitations of Pre-Cambrian Nomenclature in the Saint Lawrence Basin" (Abstract), *Bull. Geol. Soc. Am.*, Vol. XXIX (1918), pp. 90–91.

[*To be continued*]

Reviews

Oil Investigations in 1917 and 1918. Bulletin 49. Illinois Geological Survey, 1919. Pp. 144.

The volume consists of five papers bearing on the oil and gas of Illinois. The first, "Petroleum in Illinois in 1917 and 1918," by N. O. Barret, contains statistics of the economic phase of the oil industry. The salient facts, as summarized in the report, are (1) that in 1917 Illinois fell in rank from fourth to fifth among oil-producing states, due to the actual decline that same year in Illinois production, and to the enormous increase in oil production in Kansas in that year; (2) that in 1918 with further decrease of production in Illinois and a notable increase in production in Louisiana, Illinois fell to sixth place as far as quantity was concerned; (3) that evidence of the high grade of Illinois oil is found in the fact that Illinois ranked fourth and fifth in value of product in 1917 and 1918, when it ranked fifth and sixth in quantity of oil produced.

The three following papers, "Brown County" and "Goodhope and Laharpe Quadrangles," by Merle L. Noble, and "Parts of Pike and Adams Counties," by Horace N. Coryell, are reports dealing with the geology of the areas mentioned with particular reference to oil and gas possibilities. All the reports have good structural maps. In the areas described there are four possible oil and gas horizons, (1) the Pottsville conglomerate, (2) the Niagaran dolomite, (3) the Hoing sand (Silurian, just below the Niagaran), (4) the Maquoketa shale and Galena Plattsville limestone or dolomite (Ordovician). The Hoing sand has furnished the best showing of oil, but prospecting in it is hazardous, owing to the discontinuous and lenticular nature of the sand. The other formations have furnished only slight showings of oil and gas in this territory. In Warren County gas occurs in small quantities in the glacial drift; the gas probably was derived from the decomposition of vegetable matter buried in the drift, and no large amounts are to be expected.

The fifth paper, "Experiments in Water Control in the Flat Rock Pool, Crawford County," by F. B. Tough, S. H. Williston, and T. E. Savage (in co-operation with the U.S. Bureau of Mines), is a statement of investigation and work done in regard to corrective work in water control in oil wells. Various aspects of the problem are discussed, including the use of mud fluid and cement in water control. R.A.J.

Recent Publications

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—Grover, N. C., *et al.* Surface Water Supply of the United States, 1917. Part IV. St. Lawrence River Basin. [U.S. Geological Survey, Water-Supply Paper 454. (Prepared in co-operation with the states of Minnesota, Wisconsin, New York and Vermont.) Washington, 1919.]

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